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NAVAL POSTGRADUATE SCHOOL

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THESIS

LIGHT EMITTING POLYMERS ON FLEXIBLE SUBSTRATES FOR NAVAL FIREFIGHTING APPLICATIONS

by

J. D. Brisar

March 2005

Thesis Advisor: Nancy M. Haegel
Second Reader: Peter Crooker

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13. ABSTRACT (maximum 200 words)

Display technologies in the current market range from the simple and cheap incandescent bulb behind a graphic overlay to the upwardly expensive flat panel high definition plasma display. To provide a foundation of understanding for Light Emitting Polymers (LEP), samples were imaged in a scanning electron microscope. This was preformed to identify a potential method for answering questions on polymer charge mobility and diffusion mechanisms, which are currently unknown. Light Emitting Polymer (LEP) displays offer a viable alternative to the active matrix style, when an application calls for information to be sent in a simple visible format. By using the flexibility of the fabrication process, LEP displays can be applied to offer a low cost, lightweight, and durable means of communicating information during shipboard damage control and firefighting. A unique screen printing method was used in collaboration with Add-Vision, to produce a prototype that was designed, fabricated and tested for use in Naval shipboard firefighting evolutions. The application of the LEP technology to shipboard damage control was motivated by the experience gained from being both the Officer in Charge of a Naval Firefighting School and from time in the Fleet as a Damage Control Officer.

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LIGHT EMITTING POLYMERS ON FLEXIBLE SUBSTRATES FOR NAVAL FIREFIGHTING APPLICATIONS

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B.S., University of Pittsburgh, 1995

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN APPLIED PHYSICS

from the Physics Department

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

Display technologies in the current market range from the simple and cheap incandescent bulb behind a graphic overlay to the upwardly expensive flat panel high definition plasma display. To provide a foundation of understanding for Light Emitting Polymers (LEP), samples were imaged in a scanning electron microscope. This was preformed to identify a potential method for answering questions on polymer charge mobility and diffusion mechanisms, which are currently unknown. Light Emitting Polymer displays offer a viable alternative to the active matrix style, when an application calls for information to be sent in a simple visible format. By using the flexibility of the fabrication process, LEP displays can be applied to offer a low cost, lightweight, and durable means of communicating information during shipboard damage control and firefighting. A unique screen printing method was used in collaboration with Add-Vision, to produce a prototype that was designed, fabricated and tested for use in Naval shipboard firefighting evolutions. The application of the LEP technology to shipboard damage control was motivated by the experience gained from being both the Officer in Charge of a Naval Firefighting School and from time in the Fleet as a Damage Control Officer

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Last, but not least, I would like to thank the Space and Naval Warfare Systems Center, San Diego for believing in the concept of a light emitting polymer displays and providing the means to fabricate a prototype.

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I. INTRODUCTION

A. HISTORY

Over the past forty years many advances have come to fruition in the fields of chemistry, physics, and electronics. These disciplines have merged within this time due to breakthroughs, with respect to fabrication and material formulation, in the area of light emitting devices (LEDs). LEDs have been commonly associated with light emitting diodes since their conception. The emergence of this new technology of light emitting polymers has expanded the use of the LED acronyms to include: light emitting devices and light emitting displays. The impact and excitement comes from the ability to create various styles of devices whose performance can be changed by minor to major alteration in material composition, method of fabrication, and device size.

The first organic electroluminescence (EL) cells were fabricated and studied in an alternating current mode in 1953 by Bernanuse et. al.[1], and in the direct current mode in 1963 by Pope and coworkers [2]. From this point, up to the mid to late 1980s, interest in these devices centered on the use of anthracene crystals, and some emissive polymers, and the measurement of the photons given off from these structures. The photons emitted from the crystals were measured by a value called the external quantum efficiency (n_{ext}), defined as the number of photons emitted per injected electron or hole.

Although the use of the crystals produced a measurable value of the quantum efficiency, the crystal devices were bulky and thick. The thickness of the device required a large voltage bias and therefore steps proceeded to reduce the thickness of the emission layer. These efforts came to fruition in 1987 with the fabrication of a multi-layer thin film device, producing an n_{ext} of approximately 1% by the use of tris – (8 – hydroxyquinoline) Al (Alq_3) [3]. After demonstrating that thin layer devices could be constructed, research then proceeded to the optimization of various π conjugated and other polymer devices.

The first polymer light emitting device (PLED) was created in 1990 by R. H. Friend and his research group by using poly (p – phenylene vinylene), more commonly known now as PPV [4]. PPV was made by spin coating a precursor polymer onto a transparent conducting Indium – Tin – Oxide (ITO) anode substrate, thermally converting the precursor to PPV and finally evaporating an aluminum thin film cathode on the PPV[5]. This new approach to device fabrication has enabled multiple research groups to build devices which now can operate continuously for tens of thousands of hours, at a brightness comparable to current electronic display technologies. Even with comparable performance values, there are a few limitations in the way of broad scale use of PLEDs versus traditional methods. These limitations are due to the issues of polymer lifetime and a lack of complete understanding of polymer degradation and the interface with the contacts.

At a time where technology is rapidly out of date - sometimes in months - the four decade infancy which PLEDs have undergone is remarkable. As modifications in the fabrication process proceed and answers to the questions of charge motion and polymer degradation are found, PLEDs will grow into a strong adulthood and become a technology with broad application.

B. MILITARY RELEVENCE

The prototype light emitting polymer display which is being designed is provided to offer a solution to current fleet shipboard issues in the area of Firefighting and Damage Control. The importance of this solution is to provide additional options to be considered during the analysis of alternatives for future damage control communications and display technologies. Although the prototype is primarily designed for this purpose, aditional shipboard and fleet applications are envisioned.

C. THESIS OVERVIEW

Chapter I provides a brief background on the evolution of light emitting devices and its applicability to the military. To understand how both organic and polymer devices work, Chapters II and III describes the dynamics, mechanisms, and structures of how these materials produce light for a display. In order to explain the technology's use in the Navy, Chapter IV outlines damage control communications and fire party organization and the common problems experienced during shipboard damage control. These issues are then provided a solution in the final chapter, where the design, fabrication and testing of a polymer light emitting device is outlined.

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II. BASIC DYNAMICS AND MECHANISMS OF ORGANIC LIGHT EMITTING DEVICES

A. ELECTRONIC STRUCTURE

The basic electronic structure of Organic Light Emitting Devices (OLEDs) and Polymer Light Emitting Devices (PLEDs) is centered around the fact that luminescent organic materials are comprised of conjugated molecules. In a conjugated molecule, single bonds (σ) are alternated with either double or triple bonds (π) along the molecule's backbone. In single-bond molecules only σ bonds are present and therefore electrons are locked into the backbone of the structure. Alternatively double bonds consist of a σ and a π bond, and a triple bond will have multiple π bonds, which can provide a path for electron transport. These π orbitals will have a larger energy gap between the lowest and highest energy states (1 to 3 eV) which provides for potential excitation and visible luminescence.

To clearly see how σ and π orbitals contribute to luminescence, it is best to review the free electron model for a single and double bond conjugated molecule. In a system of conjugated double bonds, each carbon atom has three σ bond electrons and one electron given to the π orbital for bonding. The π electron is not localized at any given point and is free to move along the length of all the π orbitals in series along the molecule. In the free electron model it is assumed that the π system is a region of uniform potential and that the potential energy rises sharply to infinity at the ends of the system (ie. a square well potential). The energy levels available to the π electrons would then be those of a one dimensional box or $E=(n^2h^2)/(8ma^2)$ [6], where a is the length of the chain between the beginning and ending double bond of the chain. The other variables in the equation are: h: Planck's constant, n: Quantum number, and m: mass of an electron.

These energy levels are divided into singlet and triplet states, with the ground state for emission for most PLED materials being the symmetric singlet (1^1A_g) state [7]. Figure 1 shows the basic processes or pathways which an electron can have following photoexcitation of a conjugated segment of the polymer or of the entire polymer molecule.

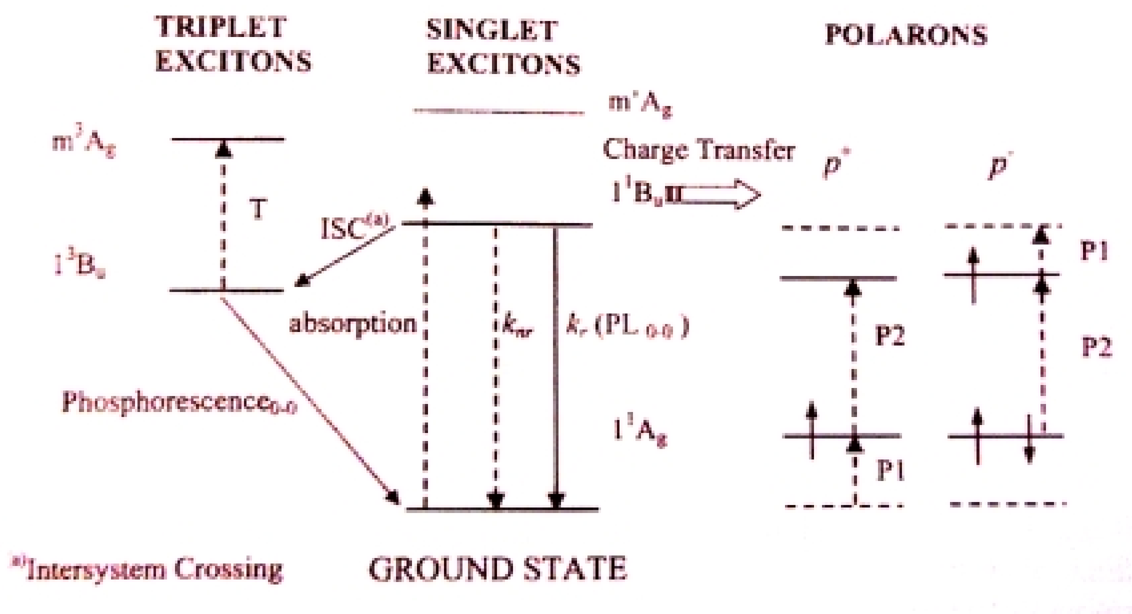

Figure 1. Basic processes following photoexcitation of a π conjugated molecule or polymer [5]

Since the material is luminescent, the anti-symmetric 1^1B_u state must be below the symmetric 2-photon 2^1A_g state. If this did not occur, the photoexcitation as expected would allow the 1^1Bu state to be filled but it would then be followed by a quick decay into the 2^1A_g level. This is not the desirable mechanism since the 2^1A_g state will nonradiatively decay into a ground state and luminescence would not occur. After photoexcitation to the vibrational structure of the 1^1B_u state, motion of the electron will occur by various means. Some of those ways are:

- Rapid thermalization of the excited state to the lowest 1^1B_u vibrational state, followed by radiative decay to the ground state.
- Charge Transfer from the 1^1B_u to an adjacent molecule or segment of the chain (dissociation of the 1^1B_u). Note that due to the speed of this process a charge transfer excition (CTE) or an intermolecular / interchain polaron pair could be generated directly from the ground state.
- Intersystem crossing (ISC) from the 1^1B_u to the lowest state in the triplet manifold, assumed to be the 1^3B_u. Even though some crystals, like anthracene, may produce a high yield via the ISC process, most π conjugated molecules or polymers do not produce such a yield.

Following photoexcitation, the desired result for OLEDs and PLEDs is obviously luminescence. The above processes are very complex in nature, so now we will describe the processes that occur with the interactions of the triplet excitons (TE) and polaron pairs with the singlet excitons (SE). Electroluminescence (EL) is the direct result of the recombination of a polaron pair in an anti-symmetric singlet to a SE.

$$p^{-} + p^{+} \rightarrow 1S^{*} \rightarrow 1^{1}B_{u} + \text{phonons} \rightarrow h\nu + \text{phonons}$$

If the polaron pair is in the symmetric singlet or triplet state, it can however, recombine to a TE instead of an SE:

$$p^{-} + p^{+} \rightarrow 3T^{*} \rightarrow 1^{3}B_{u} + \text{phonons}$$

The rates of the two reactions should be approximately equal when considering spin statistics, therefore polarons that were created by carrier injection in OLEDs and PLEDs should also generate 3 TEs for every SE. The efficiency of the devices based on fluorescent decay of SE would be suppressed depending on the ratio of this TE/SE branching. Recent studies suggest that spin statistics are not as accurate as originally thought and the anti-symmetric rate of reaction may be as much as 25% higher than the symmetric reaction [8]. Some groups have suggested that PLED devices using PPV could even have an anti-symmetric rate of 50% higher, while PLEDs, with other materials have values in excess of 50% [9].

The ability to maximize the radiative transitions and/or minimize the non-radiative transitions has started an effort to find other possible radiative mechanisms. Unfortunately some of the other mechanisms can have results, such as quenching SEs, that only create additional undesired nonradiatve mechanisms. Since the symmetric case of TE generation is still a main concern, development of OLEDs utilizing electrophosphorescence has come into development. The radiative decay of the TE in this process is due to the presence of heavy transition metals in the molecule which allows decay due to spin orbit coupling. The problem here is that some of the output may not be due directly to the transition metal doping but to the annihilation of triplet pairs to a SE.

$$1^3B_u + 1^3B_u \rightarrow 1S^* \rightarrow 1^1B_u + \text{phonons} \rightarrow hv + \text{phonons}$$

Annihilation is better known from its nuclear chemistry definition. When a particle and its anti-particle combine, they are destroyed and their energy is converted into radiation, usually a gamma ray. In the equation above, triplet-triplet annihilation is the process where two atoms or molecular entities, both in a triplet state interact, usually upon collision, to produce one atom or molecular entity in an excited singlet state and another in its ground singlet state. This process is then often followed by a delayed fluorescence, which in this case is *hv* + phonons.

The marginal success of a radiative PLED by this process is attributed to strong localization and low diffusivity of TEs in these disordered systems [10]. Another concern for radiative devices is the process dealing with interchain polaron pairs (Number 2 in the list above). The SE dissociation into interchain polaron pairs is a non-radiative case and can be caused by the applied bias on the device or various other defects in the film at the many interfaces. The generated polaron pairs, in addition to those non-radiatively decaying to the ground state, have the ability to either quench other SEs in the material, due to the their generated electric field, or they can absorb the energy from a SE. The reactions for these effects are:

$$p^{-/+} + 1^1B_u \rightarrow p^{-/+*} + \text{phonons}$$

$$p^{-/+} + 1^1B_u \rightarrow p^{-/+} + p^+ + p^- + \text{phonons}$$

The mechanisms of the interactions between TEs, SEs, and polarons will dictate the device's ability to radiate. By careful design and due consideration to the material reactions, light emitting devices have been constructed with a measure of success.

B. PHYSICAL STRUCTURE

The structure of OLEDs has changed over the years as mentioned before. These devices can currently range from single to multi-layer devices of various thickness. Figure 2 depicts a basic structure of a bilayer OLED.

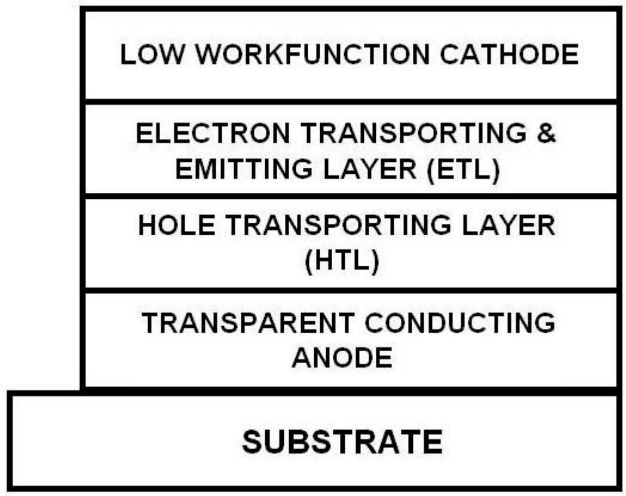

Figure 2. Basic structure bilayer OLED [5]

The anode sits on top of the substrate, which can be glass or plastic. The anode for most applications is transparent so that emitted light can be seen from the device. The most common transparent anode is indium tin oxide (ITO). Since ITO treated glass has been a major part of the display industry, the facilities needed to produce and handle the high quality ITO treated glass are already in place. Commercial batches of ITO-coated glass are normally characterized by square or sheer resistance, material roughness, and layer transparency, all of which have direct effects on the functionality and durability of the device [11]. The ITO, however, is not a homogenous mixture of its base components but is a non-stoichiometric combination of In, InO. In_2O, In_2O_3, Sn, SnO, and SnO_2. This combination places as much oxygen in the ITO as possible in order to drive the work function of the material upward. If the ITO is saturated with oxygen, the work function will increase by as much as 0.6 eV, which can increase the efficiency and brightness of the device. ITO, like all materials in LEDs, is not without its problems. In the most common configurations, known as the "cathode on top" setup, light is emitted first through the ITO and then through the glass. Unfortunately there is a strong coupling of the emitted light to the evanescent mode inside the glass that leads to extremely high light losses [12]. Although ITO is the most common transparent anode material, some of the other materials currently in use are polyaniline (PANI), poly(3,4-ethylene dioxy-2,4-thiophene)-polystyrene sulfonate (PEDOT-PSS), platinum, and zinc oxide. Like ITO, each material has its own tradeoffs and their use is widely dependent on the device application.

Deposited on the transparent anode are the layers from which the light is being emitted. This portion of the device can consist of one or more layers of polymer or other organic material. The benefit of the multi-layer approach is directly related to performance. At the interface of the cathode/anode with the light emitting layer, defects in the material are expected from the fabrication process. Multi-layers bring the barrier for hole injection at the ITO interface to a lower level and enable the recombination of electrons and holes to occur away from the cathode interface and into the bulk of the material where defect concentrations are lower. This will provide greater control over the recombination process. Due to this reason, as seen in Figure 2, the layer on top of the ITO should be a good hole transporting layer (HTL) and the material in contact with the cathode should be selected to maximize electron transport, and is therefore named the electron transporting and emitting layer (ETL).

The cathode in the basic structure has normally been chosen to be a low to medium work function metal such as calcium, aluminum, or a magnesium/silver combination deposited by e^- beam or thermal evaporation. Many sources of information exist on cathode contact materials but will not be elaborated upon here.

C. OPERATION

To further understand the interaction of these layers it is beneficial to examine the operation of the device shown in Figure 2. Holes are injected from the ITO into the HTL and electrons enter into the ETL from the cathode. Figure 3 depicts this process.

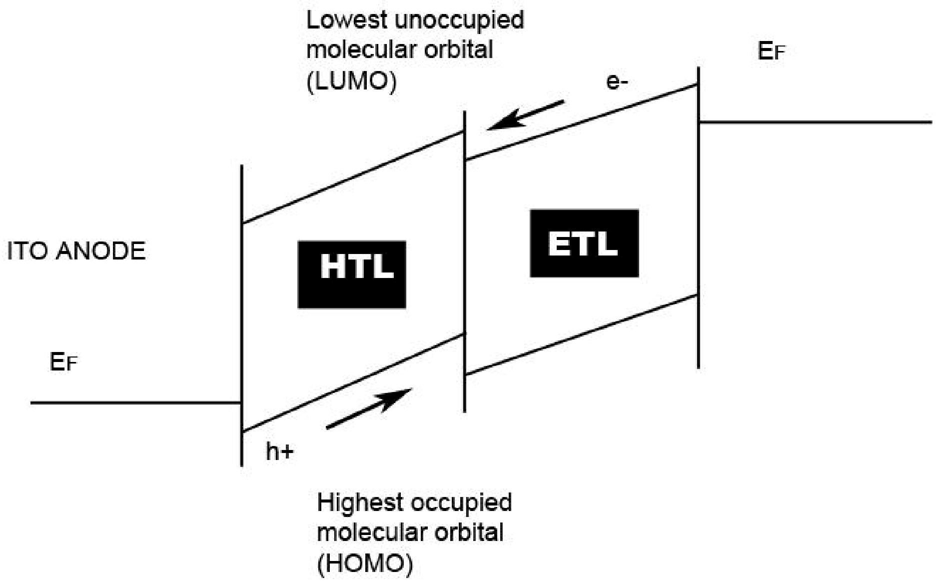

Figure 3. Basic Operation of OLED [5]

The injection for both holes and electrons is normally opposed by a triangular barrier upon penetration into the bulk of the material. In the lower current carrier injection regime, the current is determined by the rate at which the charge can proceed past the barrier, either by hopping over it due to thermionic emission, by tunneling through it, or by transport through the barrier by hopping among localized gap states. In the higher current, space-charge-limited-current (SCLC) regime, the current is dictated by the properties of the material in which it flows.

Up to this point, the text has laid out a framework which applies to both small molecular OLEDs and polymer LEDs (PLEDs). From here on we will focus on polymer devices in order to make the transition to the actual device and experimental work on polymer light emission which will be explained in sections IV and V..

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III. THE POLYMER LIGHT EMITTING DEVICE

A. INTRODUCTION

The discovery of luminescence in the polymer PPV in 1990 initiated the effort to bring this technology to maturity. The PLED is very similar in nature to its OLED counterpart but differs in electronic structure and operation, which is a direct result of how the devices are fabricated. To narrow the focus, PPV, unless noted, will be the basis for all discussion on PLEDs.

B. OVERALL REVIEW OF OPERATION

A PLED consists of a thin conjugated polymer sandwiched between a transparent anode (typically ITO) and a cathode, all of which is supported by a glass or plastic substrate. With a voltage bias applied to the device, electrons and holes injected into the polymer will then drift due to the applied field, causing recombinations to neutral states called excitons. These excitons may then undergo either radiative or non-radiative decay to a ground state, thus giving off light or not, respectively. The light emission, whose color is dictated by the energy gap of the polymer, is then seen through the transparent anode and substrate. Chemical substitution can be used in the polymer to create the desired color of emission from the device.

C. ELECTRONIC STRUCTURE

The polymer backbone is held together by sigma bonds formed by the three sp^2 hybridized electrons on each carbon atom with the last electron being the valence electron on the p_Z orbital. The p_Z orbital wavefunction is shown in Figure 4.

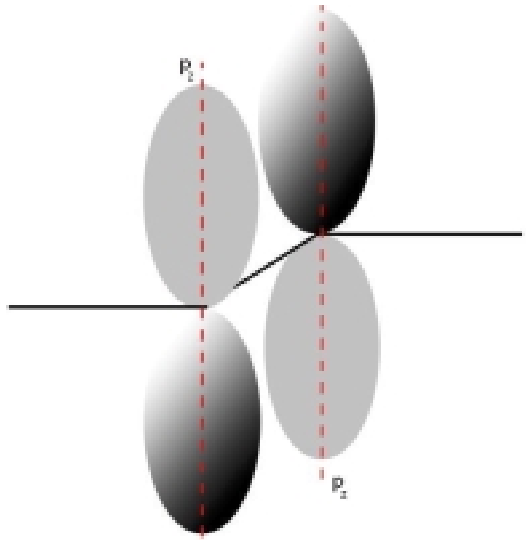

Figure 4. p_Z orbitals along a conjugated polymer backbone [5]

The p_Z orbitals in the polymer overlap to form a single delocalized π molecular orbital and an unoccupied π* orbital separated by an energy gap. Electronic transitions can then occur between the highest occupied molecular orbital (HOMO) (π orbital) and the lowest unoccupied molecular orbital (LUMO) (π* orbital).

Many models give descriptions of conjugated polymer properties, which are quite accurate for the ground state but less accurate for excited states. Interactions between repeat units of a polymer tend to be stronger and more dominant than the interactions between polymer chains, which allows the electronic structure of polymers to be viewed as one dimensional. In the one dimensional system, there is strong coupling between the electronic excitations and the chain geometry, therefore charge can be accompanied by local reorganization of chain geometry. The reorganization of the chain can lead to areas where the bond alteration amplitude is weakened or reversed. When this occurs it is called a polaron, and the polaron will have an energy level which is relaxed within the energy gap. An example of the energy states for both positive and negative polarons is shown here in Figure 5.

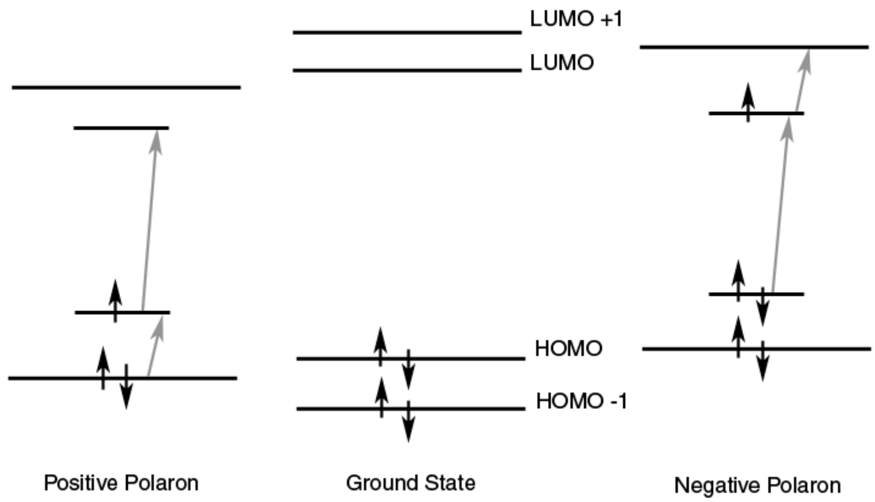

Figure 5. Electronic transitions (grey arrows) due to positive and negative polarons. Occupation of electronic energy levels is denoted by black arrows. Ground state is shown as a reference. [5]

Photoexcitation in the conjugated polymer cannot just be looked at as the excitation of an electron from the HOMO to LUMO. The interaction with the polymer lattice and the coulombic attraction between electron and hole needs to be addressed as well. In semiconductor physics, electrons and holes are delocalized in all three dimensions; therefore overlap of orbitals is small, which leads to the coulombic binding energy being smaller than the thermal energy at room temperature. A conjugated polymer is different: the electrons and holes are confined within the polymer chain, which therefore creates a larger binding energy that is dictated by the level of delocalization along the chain [13,14].

Singlet excitons are a molecular excited state which will couple strongly to vibrations of the polymer chain, giving a series of vibrational sidebands which can be observed in the absorption and emission spectrum. These excitons can extend over more than 10 repeat units along the chain as long as defects do not distrupt the conjugation of the polymer chain. The singlet exciton has a radiative decay that is an important process for the operation of PLEDs. Radiative decay competes with all the non-radiative processes such as quenching of excitons by defects, exciton dissociation, and intersystem crossing to form triplet states [5]. The photoluminescence quantum efficiency (PL_{eff}), which is the number of photons emitted per photons absorbed, will then be:

$$PL_{eff} = b\ (\ k_r\ /\ (k_r + k_{nr}))$$

where k_r (k_{nr}) is the radiative (non-radiative) rate and b is the fraction of absorbed photons which generates singlet excitons. As an example, PPV has a PL_{eff} of 0.27 with an overall decay rate (k_r +k_{nr}) of (320 ps)$^{-1}$, which shows that the efficiency can be accounted for solely by the competition between radiative and nonradiative decay. If a material has a b value that is close to 1, then it would imply that in the material singlet excitons are the predominant product of photoexcitation [15]. It should be noted that even though singlet excitons are primarily localized on a single polymer chain, there can be some hopping between chains by a process known as Forster transfer.

D. SINGLE LAYER PLEDS

Single layer devices were the first to be created and have continually been studied since one only has to consider reactions within a single material. The first single layer devices that were fabricated were inefficient, therefore interest has centered on the internal efficiency of the polymer (n_{int}). The internal efficiency is defined as the number of photons generated within the emissive layer per charge carrier flowing in the external circuit:

$$n_{int} = PL_{eff}\ (f_{\ singlet})\ (n_{\ recomb})$$

where $f_{singlet}$ is the fraction of excitons generated in the singlet state in the LED (taken to be 0.25), and n_{recomb} is the number of recombination events taken place in the LED per charge flowing in the external circuit. For the electroluminescence to be efficient within the device a few factors need to be present. First the material must be highly photoluminescent, secondly it must have closely balanced rates of electron and hole injection, and lastly one must ensure that a large proportion of the injected charges recombine within the device rather than escaping to the opposite electrode [5].

The second and third factors listed above can be easily seen by considering the balance of charge injection. If the electrons being injected into the polymer layer have a higher barrier to overcome than the holes that are being injected from the anode, the current will be comprised mostly of holes that do not recombine. The more recombination does not occur, the more the efficiency is driven downward.

The large range of materials currently being used for single layer devices has brought uncertainty to the current–voltage and current–luminance characteristics of the devices. This is compounded by the lack of information about mobilities, doping and recombination mechanisms, and the possibility of interfacial layers at the polymer electrode interface [5]. To overcome some of these issues, multi-layer devices have been introduced.

E. MULTI-LAYER PLEDS

In the basic structure of OLEDs it was mentioned that materials can be used next to the contacts to solely promote either electron or hole transport. Multi-layer devices make use of this concept to overcome the problems encountered in its single layer counterpart.

The first two-layer device, reported by Brown et. al. [16], introduced an electron transporting layer (ETL) between the conjugated polymer emissive layer and the cathode. Figures 6 and 7 shows a schematic of a bi-layer device and the resulting energy level diagram.

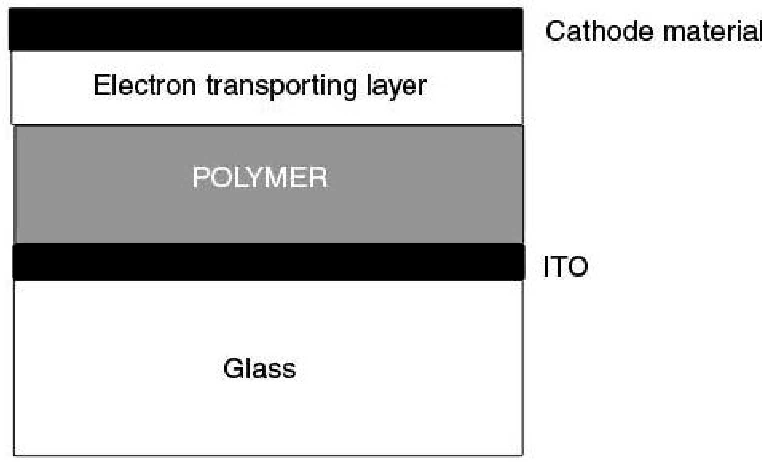

Figure 6. Schematic structure of a polymer LED incorporating an electron transporting layer [5]

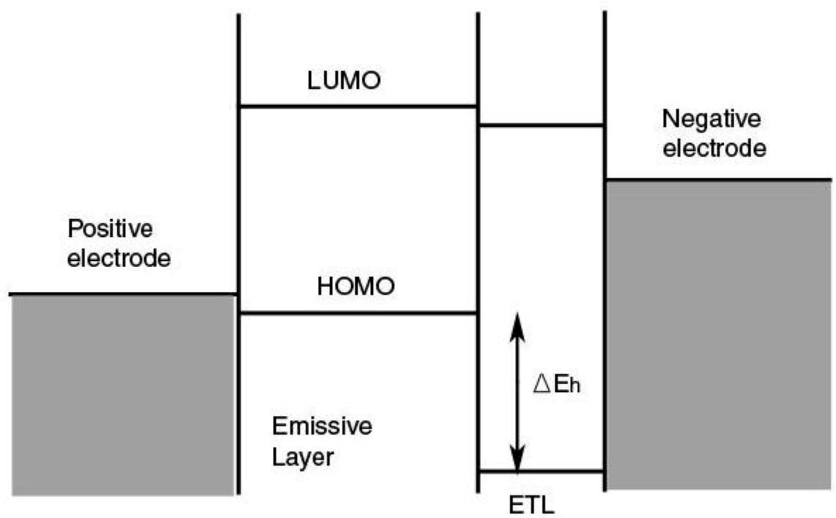

Figure 7. Schematic energy level diagram for the device shown above [5]

The addition of the ETL can increase the quantum efficiency of the device by up to one order of magnitude. This increase is due to overcoming the problem of a greater hole injection then electron injection as seen in single layer applications. The ETL layer does not actually increase electron injection but rather sets up a secondary barrier that holes have to overcome. By reducing the number of holes that move through the device without recombination, a higher charge density will be formed at the interface; thus the probability that recombination will occur increases. This process also will alter the electric field being generated in the device in a way that promotes electron injection. The ETL will also shift recombination away from the contact interface where radiative decay is reduced and move it to a location inside the bulk material of the polymer where there are fewer defects.

F. TRANSPORT AND RECOMBINATION

A vital mechanism to the operation of PLEDs is the ability of electrons and holes to traverse the polymer and recombine. Although the difficulties with injection barriers are understood, the processes of transport are less familiar. These processes can dictate the electrical properties of the device and currently still require intensive research. Transport processes are described by the current density (J) due to a single carrier type by:

$$J = n \, e \, \mu_{eff} \, F$$

where F is the applied electric field, μ_{eff} the effective mobility of electrons and holes and n is the total number of charge carriers present per unit volume.

Traditionally there have been a multitude of methods to calculate charge mobility, but unfortunately polymer LEDs are not a traditional material. Using time of flight (TOF) measurements can be problematic due to the dispersive nature of transport through the polymer. There have been attempts to extract values of mobility from measurements of metal–insulator–semiconductor field-effect transistors using a conjugated polymer as the semiconductive layer. This method of mobility measurement is dictated by the dopant levels of the polymer and therefore undoped polymer will not show a field effect [17]. It is not clear if the extracted mobility values from the field effect measurements are relevant to the operation of LEDs due to the difference in electric field, charge densities, and trap filling. Further complications may also arise due to the insulator layer close to the active region in the field-effect transistor and to the different direction of transport relative to the plane of the polymer film.

Mobilities of charge carriers, it is thought, may be found from the external device characteristics of the conjugated polymer. One approach is to study the transient response of the light output in the polymer LED to an applied voltage pulse [18-20]. The delay between voltage turn-on and light turn-on can give some measure of the transit time of carriers in the device. Both values of turn-on will be discussed in more detail in a following section. This method has to be performed carefully to ensure that the recombination of injected carriers is being measured and not that of the recombination of injected carriers with extrinsic or trapped carriers within the device [18]. The recombination rate (R) is related to the density of the electrons and holes (n and p) by:

$$R = n\, p\, \gamma$$

where γ is the recombination rate constant.

A theory for recombination in a system where the mean free path of a carrier is small shows that the recombination rate constant can be found by:

$$\gamma = (e / \varepsilon)(\mu_e + \mu_h)$$

where μ_e and μ_h are the mobilities of electrons and holes respectively [21]. This theory, in conjunction with the turn-on voltages, can be used to estimate the position of the recombination zone, and by using the emission spectrum of multi-layer devices, the amount of recombination in each layer [22]. Other methods also exist which use the absorption of both singlet and triplet excitons along with a knowledge of the optical cross section to estimate density and the average mobility.

G. CHARGE INJECTION BARRIERS

The current density that was discussed in the previous section can also be affected by the charge injection properties of the interface between the polymer and electrode and by the barriers that are present against injection. It had been thought that the barrier for charge injection was mainly dependent on the work functions of the contacts and the HOMO / LUMO energy levels in the polymer. This was based upon the belief from rigid band theory that the charge injection voltage is determined from the difference in the same contacts' work functions or the built in potential (V_{bi}) [23,24]. This has recently been found to not be entirely correct and may only be true in an extreme case where there is an ohmic or barrierless contact for the injection of the majority carrier. To correct the problem, the V_{bi} must be altered by a correction factor to accurately determine the injection voltage [25]. A nonideal ohmic contact, which creates an extra energy barrier for injection of charge carriers across the interface, is the cause of the difference. Therefore, in polymer LEDs, the fabrication of the contacts and how the contacts interface with the polymer will dictate what energy barriers are present.

1. Interface Dependence

The type of interface, whether it be Metal on Polymer (MOP) or Polymer on Metal (POM), will be the cause of the shift in the energy barrier leading to an increased or decreased V_{bi} . The work function contribution to the barrier, as mentioned above, is solely material dependent and is dictated by the contact material selection and the polymer. What creates the variation is not a matter of materials but of the fabrication process itself. The POM contact is created by depositing a polymer, by spinning or similar method, on top of the metal. The MOP is made by evaporation, or similar method, of a metal on the polymer. Although both processes create a polymer/metal interface, the fabrication process that is used for each will create an interface quality that is quite different. Evaporated metal molecules will be able to penetrate into the polymer. Since the metal atoms can diffuse into the polymer, shown to be up to several nanometers [31], the π electrons in the polymer have a direct metal contact. In POM contacts however, this direct metal contact does not exist. The process for placing the polymer on the metal does not afford the ability for diffusion into the contact, creating a separation of the metal and the π electron backbones. This separation is increased as the solvent used to apply the polymer to the metal evaporates off. The evaporation produces holes or empty space within the polymer leading to further separation at the interface. The empty space may allow the polymer chains to relax during operation, which will further break down the contact further and lead to decreased charge injection [5].

When looking at both types of contacts, the metal on polymer, as expected, will have better injection efficiency than its counterpart, which means that at the POM contact the observed energy barrier will be higher than the intrinsic barrier [5]. The observed energy barrier Φ is defined as the sum of the intrinsic energy barrier Φi and a contact-dependent component $\Delta\Phi$ as follows:

$$\Phi = \Phi_i + \Delta\Phi \quad [32]$$

The definition put forth above lets the minimum energy required for charge injection be represented by Φi , which will be dependent on the materials present, where $\Delta\Phi$ is the component that is dependent on the quality of the interface and therefore on polymer morphology.

The overall effect of this, in addition to a change in the built-in potential needed for injection, is that the device has directionality. The device when operated under forward bias will be different than the operation under reverse bias. The cathode can be expected to have a contact dependence $\Delta\Phi$ close to zero, whereas the anode will have a value depicted by morphology. The forward bias case will have a higher energy barrier at the POM contact for hole injection than the reverse bias case will have at the MOP contact. The operation of the device in forward bias will then have a lower current than in the reverse bias operation, where hole injection is at the higher quality MOP contact. This effect will directly influence the voltages needed to operate the device.

H. TURN ON VOLTAGES

PLED devices are operated by applying a bias across the device. This bias is called the turn-on voltage and is separated into two distinct parts. The first part is the voltage needed to start injection of current into and through the device ($V_{I\text{-}ON}$) and the second is the voltage needed for the device to emit light ($V_{L\text{-}ON}$). In the PLED the carrier injection efficiency is dominated by the carrier injection rate and the carrier mobility only comes into play if the carrier injection rates are close to being equal. $V_{L\text{-}ON}$ should then be considered to be determined by the minority carrier injection which is confirmed by data from MEH-PPV devices using ITO / PEDOT as the anode and calcium as the cathode

[26]. Therefore when the device is operated between $V_{I\text{-}ON}$ and $V_{L\text{-}ON}$ it is a single carrier (electron) device and the voltage difference between the two is the value of the energy barrier for hole injection.

1. Current Injection and Light Emitting Voltage

The voltage $V_{I\text{-}ON}$ has been related to V_{bi} which was introduced in the previous section and can be seen in the relation:

$$V_{I\text{-}ON} = V_{bi} = \Delta\Phi + \varphi$$

where $\Delta\Phi$ is the work function difference and φ is the correction term determined by the quality of the contact, which is also temperature dependent. When an ideal ohmic contact is being used $\varphi = 0$ and $V_{I\text{-}ON} = \Delta\Phi$, so when operating between the two turn on voltages, φ will be the same as the energy barrier for electron injection [5].

The voltage for light emission will be set by the fabrication of the device more than its material type. Since $V_{L\text{-}ON}$ is determined by the hole injection ability of the anode (POM contact during forward bias) the contact quality will determine the energy barrier for hole injection, and therefore is more sensitive to the polymer film morphology. As in the previous examples, by using different solvents to place the polymer on the device and thus increasing or decreasing the quality of the contact interface, one can either raise or lower $V_{L\text{-}ON}$.

I. DEVICE QUANTUM EFFICIENCY

In the beginning of the paper, the topics of external and photoluminescence quantum efficiency were described. The definitions of these terms are clear, but the actual values for different devices are still matters of intense debate. This is because the exact mechanisms are not fully understood. Although not all aspects and theories can be examined, two of the most controversial will be discussed and reviewed. The two are broken up into the "traditional" thought that follows from the original PLED community, and the second from recent arguments on the topic.

1. Traditional Belief

The efficiency of the device has as much to do with how the polymer is produced and placed in the device as it does with the electrical properties of the material. Depending on the concentration and the solvent that is being used, the polymer can form aggregates. In simplistic terms, dilute solutions will provide distance between polymer chains, while more concentrated solutions will decrease the distance. As the distance decreases, the polymer will aggregate into structures that are entangled. The aggregates can have interchain interactions which will alter the behavior of the original polymer solution. Since the interchain interactions are short distance forces, only when the polymer chains begin to aggregate are the forces of concern. The aggregation is directly linked to the quantum efficiency since for optimum conditions to occur, the polymer chains need to be stretched in order for better conjugation of the π electrons. Thus interactions between chains that have undergone aggregation will quench the π electron conjugation. This conjugation of delocalized electrons in the p_Z orbital has been the foundation of PL / EL and the factors that influence the quantum efficiency.

2. Quantum Efficiency: A New Perspective

Studies of the quantum efficiency have been focused until recently on the argument above. New research is suggesting that the formation of aggregates may not necessarily be unwanted. The first step is that many groups have made efforts to modify the polymer structure at the molecular level with the intention of suppressing chain interaction during aggregation to boost quantum efficiency [27]. If the interchain forces can be overcame or nullified, the delocalization of electrons along the polymer backbone can proceed as expected. Other individuals have just challenged the traditional thought outright. It is suggested that aggregation of the polymer chains can actually enhance the quantum efficiency and that the quantum efficiency has a correlation with the emissive spectrum and the polymer morphology rather than the thickness of the polymer film. [28] The research in this area is much like that of all polymer LEDs. There are cases that exist to support the theory of aggregation dependence on efficiency, as well as those that support a thickness (spin rate) dependence, but no overall experimental results can be applied to every device. Until more work can be done, to provide information that is still unknown, the ability to formulate a firm relationship to quantum efficiency can not occur. The efforts to put forward new theories do however provide additional keys to solving the puzzle.

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IV. POLYMER ELECTROLUMINESCENCE AND CATHODOLUMINESCNECE IMAGING

A. INTRODUCTION

Experimental work with light emitting polymers has focused on demonstrating the observation of electroluminescence and cathodoluminescence in the scanning electron microscope. The previous section introduced the theoretical mechanisms and most likely mechanisms for polymer luminescence. With this in mind, the purpose of this section is twofold: first, to introduce an experimental method of charge imaging and transport, which previously has provided data on the diffusion and drift in semiconductor materials [36], and to explore the application of the method to polymer materials. Secondly, the imaging will be used in conjunction with voltage and current measurements to study polymer response and luminescence behavior under varying conditions. The imaging data will then be used as a basis for future research.

B. EXPERIMENTAL SETUP AND METHOD

The equipment which is being used is a combination of three separate technologies that have been brought together in order to image individual charge carriers and light emission of a device material. The setup consists of a JEOL 840A Scanning Electron Microscope (SEM), an optical microscope, and a KX32ME cooled Charge Coupled Device (CCD) camera. The concept is to use the charge generation from the SEM to create charge carriers within a material in order to initiate luminescence. The luminescence is then spatially observed by the CCD camera with the resolution obtained from the optical microscope. The following tables provide some additional information on the specifications of the three primary components.

Variable accelerating voltage; 200 to 40,000V
Variable probe current; 1x10E-8 to 1x10E-12 Amps
Maximum sample size of 6" in any one dimension
Working distances; 8 to 48mm
Sample rotation; 360º
Sample tilting 90º
Variable magnification; 10x to 300,000x
Maximum resolution; 10 nm
Secondary and Backscattered Electron detectors
Equipped with EDS capable of detecting Carbon and forming X-ray maps of composition; composition to within 0.1 wt%
Integrated digital imaging system
Noise reduction through frame averaging
Image capture and export in electronic form (TIFF
Low cost, medium quality thermal printouts
High quality, medium cost Polaroid type 55 film containing both negative and positive

Table 1. JEOL 840A SEM specifications [37]

Array Size (pixels)	2184 x 1472
Pixel Size	6.8 x 6.8 microns
Imaging Area	14.9 mm x 10.0 mm
Linear Full Well (typ.)	55,000 e-
Dynamic Range	77 dB
CTE	0.99999
QE @ 400 nm	50%
Peak QE (typ.)	85%

Table 2. Eastman Kodak KAF-3200ME CCD Image Sensor (within Apogee KX32ME) [38]

PC Interface	PCI controller card (proprietary)
Digital resolution	14 bits @ 1.3 MHz
Download time (typ.)	4 seconds
System Noise (typ.)	7 e- RMS
Pixel Binning	1x1 to 8x63 on-chip
Frame Sizes	Full frame, software-selectable subframe, focus mode
Exposure Time	30 milliseconds to 10,400 seconds (10 millisecond increments)
Cooling	Thermoelectric cooler with forced air. Maximum cooling 30-35° C below ambient temperature
Temperature Stability	0.1° C
Dark Current (nom.)	0.1-0.2 e-/pixel/sec (-15° C)
Camera Head	Aluminum, hard black anodized. 4.6” Dia x 2.4” (11.7 cm dia. X 6.1 cm) Weight: 1.5 lb. (0.7 kg) Standard T- or C-thread interface
Operating Environment	Temperature: -30° to 80° F. Relative humidity: 10 to 90% noncondensing
Cable length	Standard: 15’ (4.5m)
Power requirements	25W maximum power with shutter open and cooling maximum. Power supplied by PC backplane.
Shutter	Melles Griot 42mm iris
Back focal distance	0.69” (1.75 cm) (C-mount parfocal)
Remote Triggering	TTL input to PC controller allows exposure start within 100 ns of trigger for applications requiring precise synchronization of exposures to external events.

Table 3. Apogee KX32ME Camera Performance [37]

The system is constructed by having the optical microscope entering into the right side of the main SEM chamber with the CCD camera attached to the microscope outside the SEM. A picture of the modified SEM can be seen in Figure 8.

Figure 8. SEM, Optical Microscope, and CCD Camera

1. Charge Coupled Device Camera

The CCD camera was initially designed for applications in astronomy and optimized to capture images of distant stars in the vast black background of space. The use of the CCD in this application is merely a change in the referenced values of distance and size. In astronomical use, the light source is of immense size and the distance from the imaging equipment is great, therefore the received light appears to be quite small. What is being done in the SEM application is the imaging of a light source on a device that is smaller than the visual acuity of the naked eye, but the distance between the sensing equipment and device is orders of magnitude smaller than in astronomy. The CCD cannot discriminate between a small light source that is close and a large light source that is far away. This enables the imaging of light sources on the scale of microns or below, as if they were stars in the night sky. This method will preserve the spatial information of the charge recombination that is being imaged [36].

The CCD is a silicon chip whose surface is divided into light sensitive pixels. An image is formed as an electronic representation on a computer when photons that are incident on the plane of the chip create electron-hole pairs. The charge carriers, induced electrons, are collected by potential wells that are formed at each pixel site. The number of the collected electrons will not be linearly dependent on wavelength but will be dependent on light level and the set exposure time. The electronic image is then viewed and analyzed with a software application from Diffraction Unlimited called MicroCCD™. The sensitivity of the CCD camera is in the range of 300 – 980 nm and is shown in Figure 9.

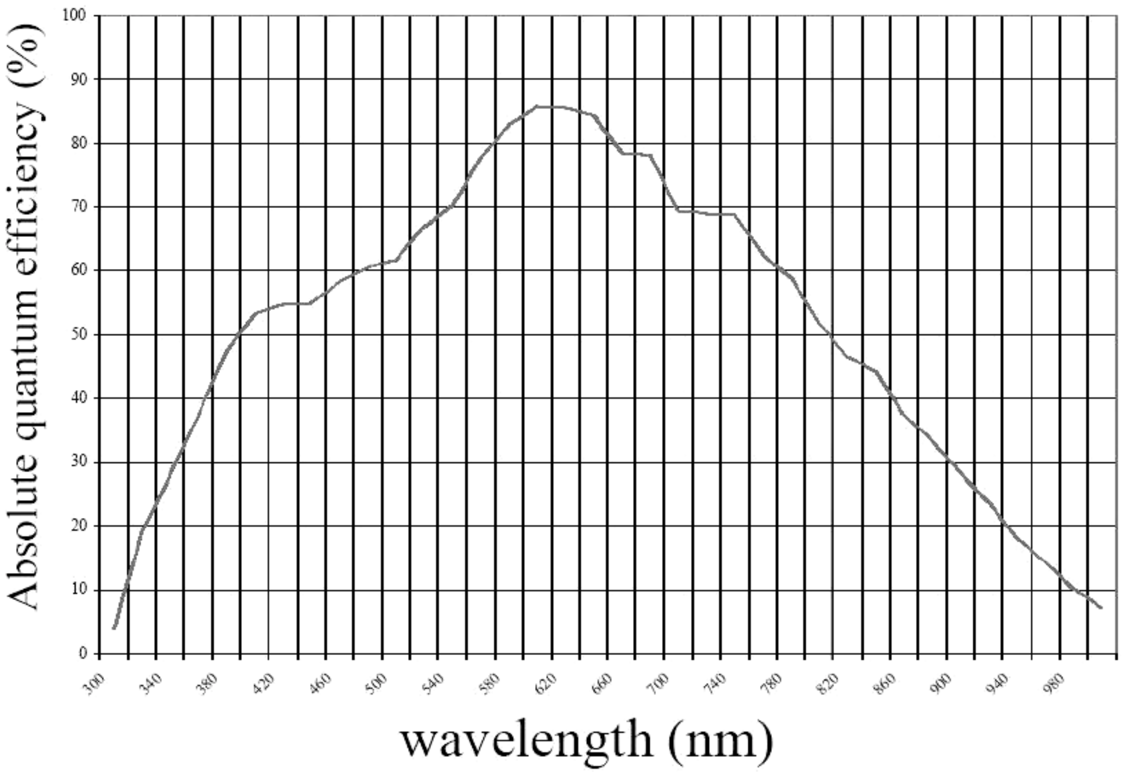

Figure 9. Sensitivity of the CCD camera [37]

C. SAMPLES AND IMAGING

The polymer samples were spin coated onto glass that had gold contacts placed on it by evaporation. The samples were made by Janelle Leger and are of a MEH PPV luminescent polymer being formulated by the Carter research group at the University of California Santa Cruz.

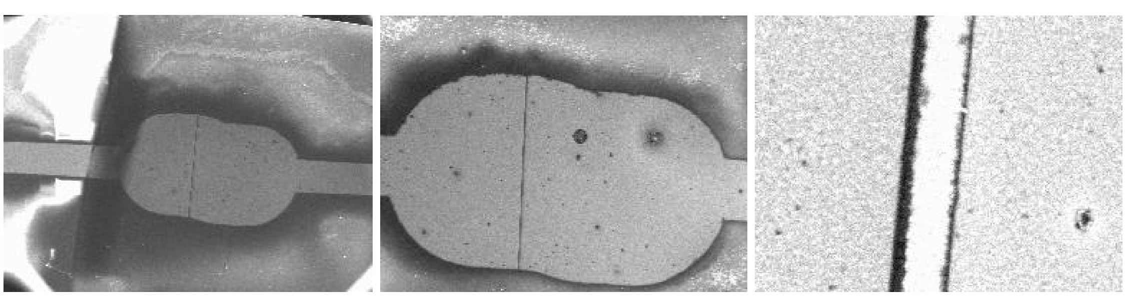

Figure 10. MEH PPV polymer sample (left to right: 10X, 19X, and 160X magnification)

Figure 10 shows the spin-coated polymer on top of the contacts that were evaporated onto a glass slide. The gold contacts are extremely thin and were connected to the voltage source by the use of silver paste. A current meter was used to monitor the current across the sample, to ensure that the circuit loop was closed, and a bias was placed across the contacts.

The voltage that was needed to produce electroluminescence (EL) in the polymer sample varied from 3.0 to 10 Volts, with accompanying currents just under 1 μA to 300 μA. This range of values is due to the use of multiple samples that had different resistances. The resistance values were affected by the thickness of the polymer, the arrangement of polymer aggregates attributed to mixing of the polymer with solvent for spin coating, and the sample's hydrophilic nature which degraded the polymer as water was absorbed from the surrounding environment.

The picture shown in Figure 11 was the first image captured of the polymer's EL.

Figure 11. MEH PPV electroluminescence under 3.5V bias (2000X Magnification)

As can be seen, the EL is irregular and is not uniform throughout the polymer. The spatial non-uniformity can be better seen by viewing the EL with respect to EL intensity, allowing each color to depict varying brightness.

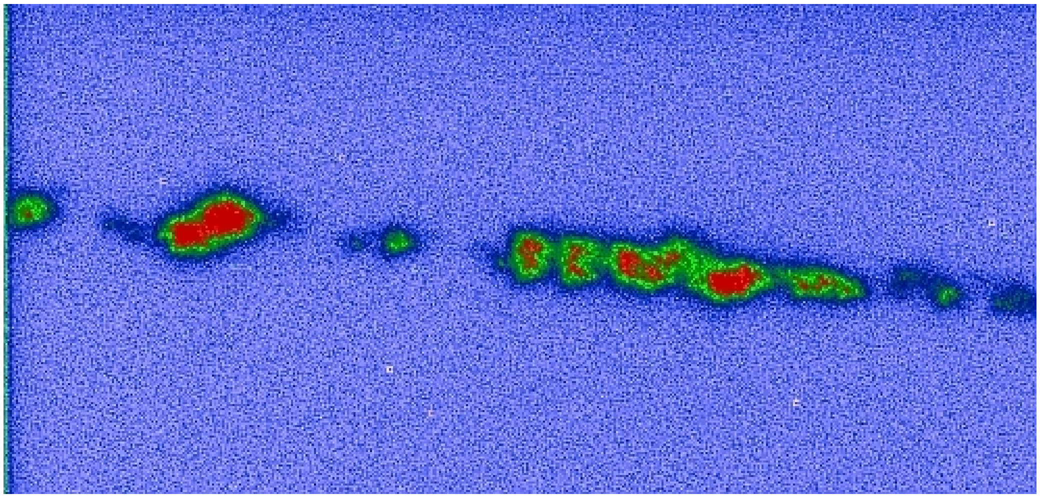

Figure 12. EL viewed with respect to intensity (2000X Magnification)

The only way to reduce the non-uniformity in the sample is to increase the bias above the amount needed to initiate EL. The increased brightness will give the appearance of uniformity, but the EL is still non-uniform.

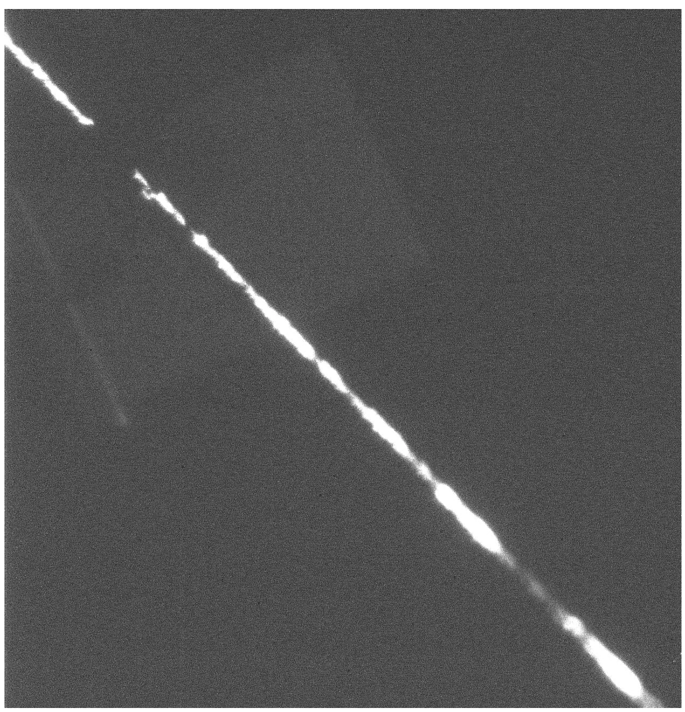

Figure 13. Polymer EL under 20V bias (2000X Magnification)

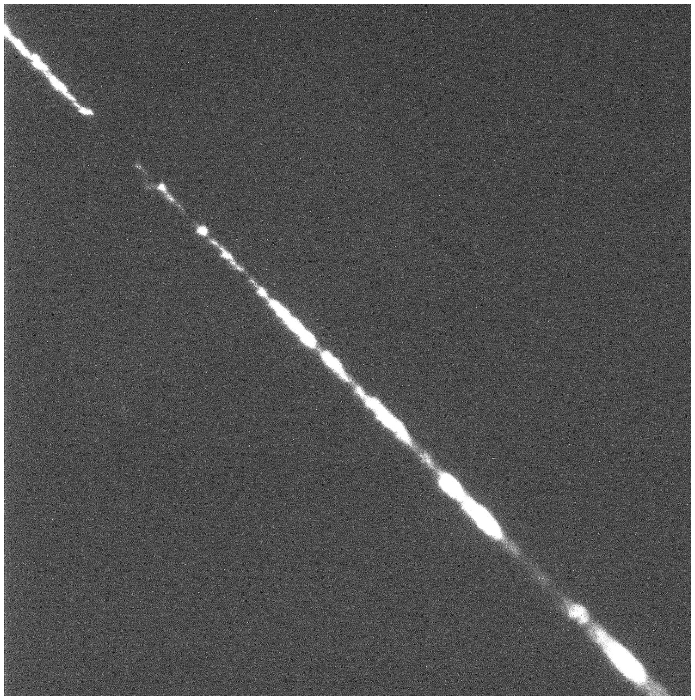

Figure 14. Polymer EL under 15V bias (2000X Magnification)

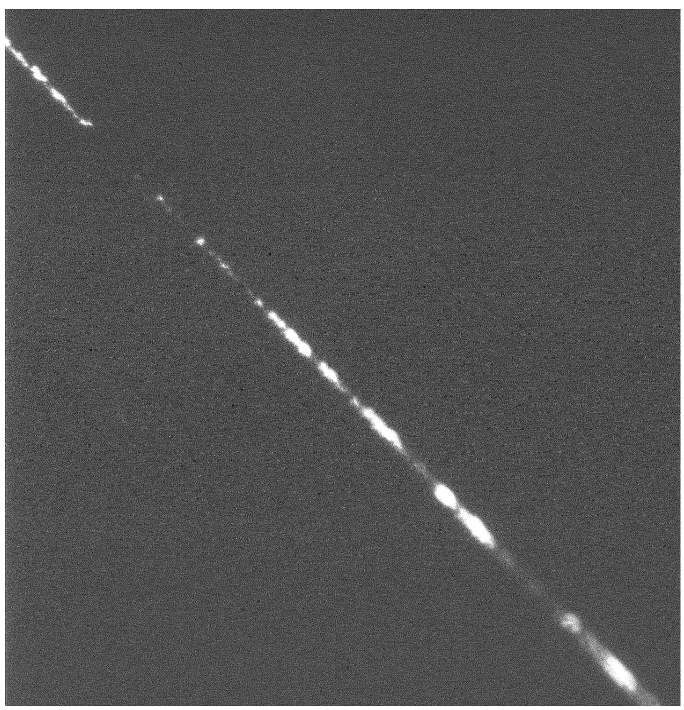

Figure 15. Polymer EL under 10V bias (2000X Magnification)

Once the EL was explored with respect to bias, the next step was to see if any difference occurred or if there was a shift in location of the EL as a function of bias direction. Since both contacts are of the POM style, there should be no directionality in the device since the energy barriers for electron and hole injection will be the same in either direction. What was found during multiple experiments was that changing the bias from +3.5 V to -3.5 V did have an effect within the device. The time required for EL to be observed was instantaneous in positive bias but took minutes in the negative case. Additionally, to achieve the same EL brightness the voltage had to be increased, -5.5 V to have an EL level comparable to 3.5 V. What also was discovered was that switching bias back and forth between 3.5 and -3.5 V would affect the positive bias case. Instead of an instantaneous EL, the timeline will begin to expand according to how long the negative bias was on. The transient behavior is a key issue for light emitting polymer material and most likely associated with space charge and trapping phenomena. The observation of spatial resolved EL in the SEM will allow future time resolved studies of EL emission and its interaction with the electron beam.

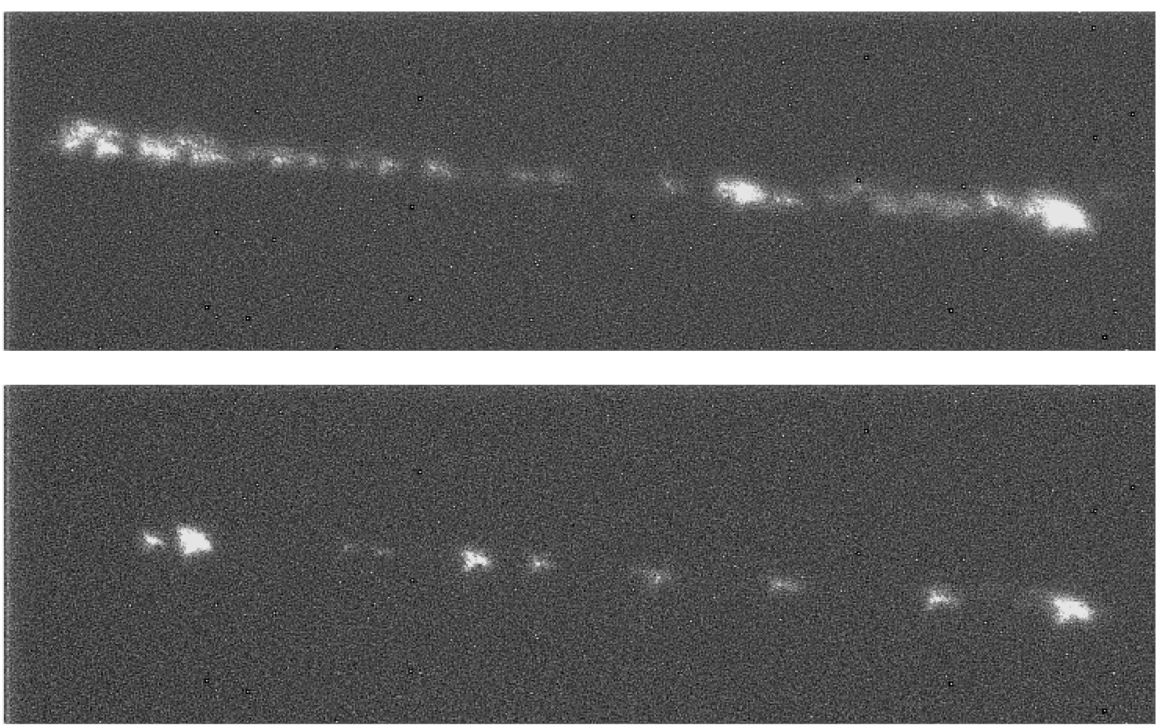

Figure 16. Top: 3.5V bias Bottom -3.5V bias (identical time of bias on 30 seconds)

The location of the EL spots was identical in both forward and reverse bias cases. What was unknown was the actual placement of the EL inside the gap between the contacts. To discover the relative location, the SEM electron beam in picture mode (PIC) was used. PIC mode of the SEM spreads the probe current over a rectangular area instead of an individual point. The gap between the contacts was approximately 30 μm. The expectation was that the polymer between the contacts would have a different response to the electron beam than the polymer on the contacts. This is because the use of the SEM beam to produce cathodoluminescence (CL) is strongly dependent on sample height. Since the polymer in the gap sits directly on the glass, compared to the polymer sitting on top of the glass and gold contacts, a different intensity of CL would be expected. Figure 17 shows the polymer response to the SEM beam. The image provided a noticeable region of contrast that, when measured, was approximately 30 μm. Since this number matched a previous measurement of the gap size, it can be accepted that what is seen is the gap between the contacts. From the image it can also be seen that the polymer EL is in the middle of the gap and not along either of the contacts.

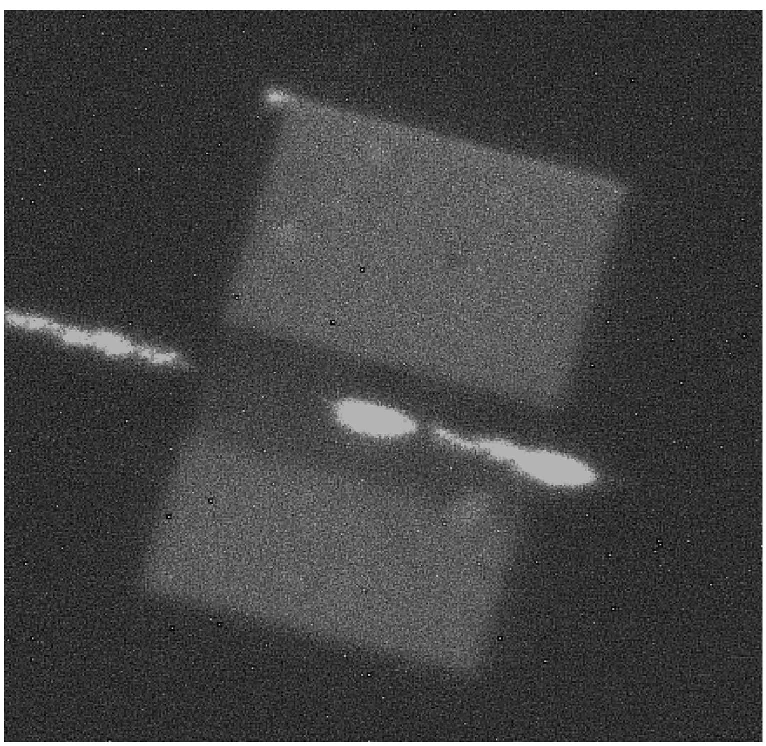

Figure 17. SEM in PIC mode for EL location (2000X magnification)

This is to be expected sense since the evaporation of the solvent after the spin coating process would produce minor amounts of open space between the polymer and the contacts. These defects at the interface would then lead to reduced EL in the near-contact region. The width of the EL emissive area was approximately 2 to 8 μm depending on the location being measured.

1. Electron Beam CL and Effects

The experimental setup has been shown to be effective for imaging the EL of the polymer, as seen in Figure 17, and has demonstrated that the electron beam can independently induce polymer cathodoluminescence. What was not known, is if the electron beam would have any interactive effect on the EL of the polymer. The SEM can be operated in both SPOT mode, placing all probe current at one spot (Fig. 18), or PIC mode, where the probe current is scanned or spread out into a box (Fig. 17) or line (Fig. 19). All three of these were used in various ways in an attempt to affect the EL. Figure 18 shows the effect of the beam close to the EL of the polymer and when the beam is directed on top of the EL.

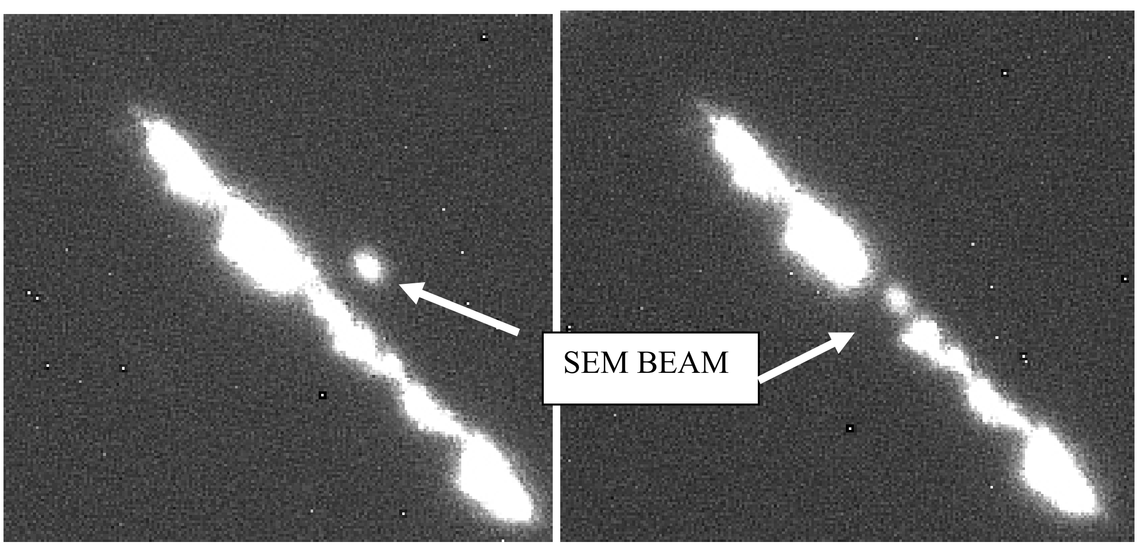

Figure 18. Effect of SEM Beam cathodoluminescence on polymer electroluminescence (Probe current 3 x 10^{-9}, 12KV, 2000X magnification)

The SEM beam's induced cathodoluminescence in the polymer on various experimental runs did not interact with the EL until the beam was placed directly on top of the EL region. When this was done, an immediate quenching was observed. The result raised questions as to whether the quenching was permanent or a transient. The polymer continued to produce EL in cases like Figure 17, so further investigation was needed. What was discovered was that once the SEM beam was in contact with the EL for any length of time, the EL did not return. In one case where the beam was only in contact with the EL for a short time, EL did recover a small amount, but not fully. More time dependent measurements will be needed in this area to resolve whether the quenching is a transient effect, due to injection of additional space charge, or if it can be contributed to damage of the polymer by the SEM beam. The next step was to examine if the SEM beam could continually produce CL. The SEM was placed in PIC mode and the beam was set up to scan a line instead of a box, to see what effect long term cathodoluminescence would induce.

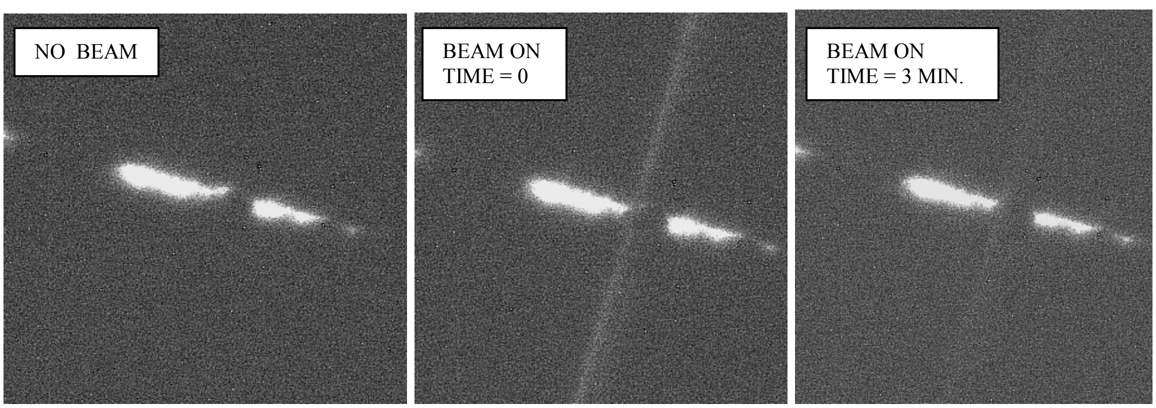

Figure 19. Cathodoluminescence over time (Picture Line Mode, 6×10^{-9} probe current, 2000X magnification)

As the images show, after the electron beam is placed on the polymer sample, EL is quenched in the area the beam is scanned. Over time, the electron beam induced cathodoluminescence will decrease, until a zero intensity of CL is observed. Images taken in SPOT mode, away from the polymer area producing EL, had the same decrease in intensity.

D. CONCLUSION

The scanning electron microscope imaging technique using a CCD camera can image both polymer cathodoluminescence and electroluminescence simultaneously. Concerns about the camera's resolution - that it would not be at a level needed for polymer EL observation - was not an issue and did not decrease the effectiveness of the experiment. The foundation for various follow-on research was made, including research on polymer EL quenching lifetimes, and SEM probe current versus cathodoluminescence lifetime studies. Overall, it was proved that light emitting polymers can be observed and manipulated by the electron beam in order to research polymer transport.

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V. NAVAL FIREFIGHTING

A. INTRODUCTION

On board a naval vessel there are many pieces of vital equipment and many personnel that perform duties from food preparation to combat missions. In order for the ship to continue its ongoing mission, it is essential to maintain material readiness and overcome shipboard damage that is sustained from both enemy action and equipment failure. Thus shipboard damage control (DC) is a major program within the Navy and advancements in methodology and technology must be implemented to increase fleet survivability.

Modernization in the DC field involves many aspects that could fill volumes but one of the most important involves communications. This section is designed to give an overview of the role of DC communications aboard a vessel. Once this foundation has been established, the application of polymer light emitting displays for use in personnel management will be introduced.

B. DC INFORMATION AND AUTOMATION: HISTORICALLY AND TODAY

Damage control information and automation in the early 1970s was limited to a manual process involving personnel passing information via soundpowered phones, plotting on damage control charts, and using local control to operate damage control and firefighting systems. Since the manual process was so slow, it was difficult to process all the information quickly and determine proper action. The effect was that the battle damage or casualty typically got worse over time, requiring even more personnel to control damage and pass information [29].

Damage control management to this day is still performed manually. On the ship all communications, damage investigations and decision-making are made by the human element, by way of radios, visual recognition of damage, and DC training. The major deficiency in this approach to DC is still the amount of time involved between the initial identification of damage to the time when corrective action is taken to control damage and restore mission capability. A secondary, but not insignificant, deficiency is the inability to know the actual conditions of ship systems prior to and immediately following actual damage. The majority of DC and fire protection systems in the fleet still use manual activation and need local control. Advances have been implemented to improve casualty response time through the remote actuation of limited damage control systems and the monitoring of fire and flooding sensor alarms on centrally-located damage control consoles and alarm panels [29].

C. SHIPBOARD COMMUNICATIONS

The ship will have built in communication circuits that are designated for specific uses. Traditionally these circuits were by soundpowered phones and shipboard announcing systems only. As time has progressed, additions have been made to include telephone systems, wireless radios and computer displays. These additions have introduced a new complexity in the control actions of the repair parties and have led to some confusion in the direction of personnel. Table 4 shows the designations of the primary DC circuits.

CIRCUIT	CLASSIFICATION	PURPOSE
JA/NET 51	Primary	Captain's Battle; all Control Stations
1JG/NET 12	Primary	Aircraft Control
3JG	Primary	Aircraft Service
4JG1	Secondary	Aviation Fuel Control
4JG2	Secondary	Aviation Fueling Forward
4JG3	Secondary	Aviation Fueling Aft
JL/NET 52	Primary	Primary Battle Lookouts
1JM	Primary	Minesweeping Operations
1JS	Primary	Sonar Control; Sonar, CIC and Bridge
1JV/NET 53	Primary	Maneuvering and Docking; Ship Control Stations
2JV	Supplementary	Engineer's Circuit (engines)
3JV	Supplementary	Engineer's Circuit (boilers)
4JV/NET84	Supplementary	Engineer's Circuit (fuel and stability)
5JV/NET 85	Supplementary	Engineer's Circuit electrical
6JV	Supplementary	Ballast Control Circuit
2JZ/NET 80	Primary	Damage and Stability Control; DC Central and all Damage Control Repair Stations (DCRS)
3JZ	Primary	Main Deck Repair Circuit: DC Central and DCRS 1
4JZ/NET 81	Primary	Forward Repair Circuit; DC Central and DCRS 2
5JZ/NET 82	Primary	After Repair Circuit; DC Central and DCRS 3
6JZ/NET 85	Primary	Forward Propulsion Repair/Engineers Circuit (electrical)
7JZ/NET 86	Primary	Engineer's Repair Circuit; DC Central; Main Engineering Control and DCRS 5
8JZ	Primary	Crash and Salvage Repair
9JZ	Primary	Crash and Salvage Repair
10JZ	Primary	Magazine Sprinkling and Ordnance Repair, forward
11JZ	Primary	Gallery Deck and Island Structure Repair
12JZ	Primary	Fire Pump Control
XJA	Auxiliary	Auxiliary Captain's Battle
X1JG	Auxiliary	Auxiliary Aircraft Control
X1JV	Auxiliary	Auxiliary Maneuvering and Docking
X1J2	Auxiliary	Auxiliary Damage and Stability Control
X2JZ	Auxiliary	Auxiliary Damage and Stability Control Circuit
X1J2	Auxiliary	Auxiliary Damage and Stability Control
X2JZ	Auxiliary	Auxiliary Damage and Stability Control Circuit
X6J	Supplementary	Electronics Service
X40J	Emergency	Casualty Communication (may be run anywhere)
X50J	Emergency	Fog Foam Circuit (AFFF)
X63J	Auxiliary	Electronic Service
WIFCIM AN/SRC-53(V)	Primary (where installed)	In Damage Control Repair Station area
WICS	Primary (where installed)	In Damage Control Repair Station area

Table 4. Typical naval surface ship sound powered telephone circuits [29]

As can be seen from Table 4, the number of circuits being used through out the ship is not miniscule by any means. The significance of this is that with the large number of voice communication circuits already in use, additional circuits are not desired and methods to reduce the number, instead of increasing the number, are a necessity.

1. Within the DC Organization

Members of the fire party send information back and forth to each other by normal voice communications through the use of voice amplifiers. The scene leader will use ship's phones, soundpowered phones or wirefree radio communications (WIFCOM) to pass information to the repair party leader [30]. The limitations of all of these methods, especially radio equipment used in fighting major fires, must be realized and accounted for. An example of equipment limitation can be seen in the radio, which is carried in a pocket of the firefighting ensemble to protect it from high heat. This can only provide limited protection, and the protection is at the price of a reduced ease of access to the radio. Exposure to the heat over time will cause a frequency shift that will render it unusable and the team will be cut off from control [30]. Equipment failure, although understood, is an ongoing issue that occurs with no warning. Efforts need to be focused not only on this, but also on the issues that can be minimized, namely failures of the human element.

D. COMMUNICATION DIFFICULTIES DUE TO THE HUMAN ELEMENT.

The sailor brings into the situation an element of risk and uncertainty that cannot be calculated by any equation. The traits that make us individuals cannot be changed like a blanket on a bed, and some mitigation to cope with the effects is needed.

The DC organization has employed efforts from the beginning to aid in this. Where installed communication is taken out of service due to fire, enemy action, or simple human error, messengers have been employed to re-establish the link between the DC team and the control station. The messengers use a written message format to relay information. This method was found to be more reliable than an oral message which can be passed on incorrectly or altered unknowingly. An example message blank is shown here:

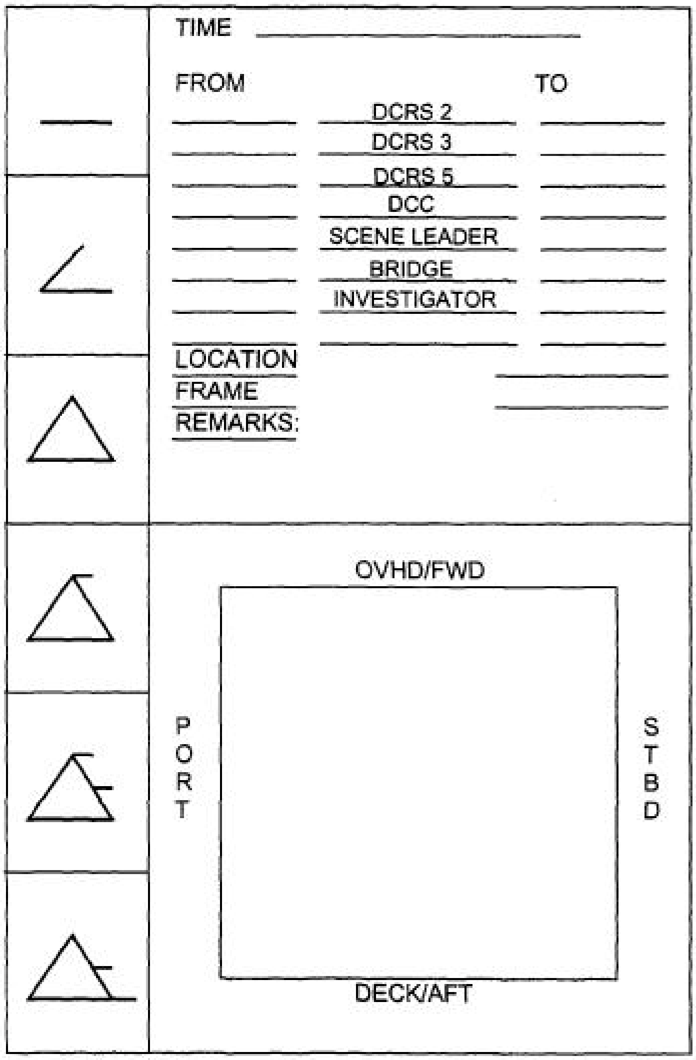

Figure 20. Message Blank [29]

The message blank uses preset visual symbols, a sort of DC shorthand, to communicate. This method was chosen to eliminate miscues and errors in repeating oral messages when primary communication methods have failed.

The issue above is also a problem in the opposite extreme, in that sailors communicate too much. When all communications are working properly, there tends to be massive use of the portable radios. With only a few channels available because of the limited capabilities of the radios themselves, every sailor with a radio needs to minimize its use in order for direction and control to occur. Unfortunately, this does not always happen, and controlling stations have to attempt to break into the circuit when sailors fail to clear a channel and want to continue talking. The main reason for this is that many individuals are taking action at once and may not consider the whole picture. Because of this, sailors just start transmitting when they desire to, causing jumbled transmissions that are mixed together. The radios that help the speed of communications, therefore, can also hinder it as well.

The last issue is the effects on the sailor operating within the firefighting teams in a severe environment. Sailors involved in DC efforts will be able to focus only on breathing, survival and the immediate task before them. When attacking a severe fire or working under stress, the attack team leader may not use the portable radios or other means of communication effectively. Under severe conditions, the controlling stations must initiate actions as necessary without depending on communication from the team combating the casualty [30]. If the scene leader needs information about the attack, he should send a messenger to the attack team. The loop here then resets to previous problems discussed above. A new method is needed to correct or at least minimize the existing limitations. To this end, the Navy wants to take advantage of today's technology to reduce the problems currently being experienced.

E. ADVANCEMENT EFFORTS

The resolution of problems surrounding naval firefighting communications does not have a single solution. The Navy has put forth the concept of an Advanced Damage Control System (ADCS) which is being installed with further developments being added as they are available. ADCS was designed to provide personnel with a graphical depiction of the location of vital DC equipment and personnel. All data will be incorporated into computerized applications of shipboard DC principles and personnel actions. The goal is not to overload the user with information but rather to provide accurate voice / data communications, displays of key useful information in a visual format that are clear and easy to understand, and transmit that data throughout the ship.

This information should reduce the workload on the DC organization during repair actions and general quarters, thereby improving rapid response tactical actions [29].

The use of ADCS at control stations is through the use of the Damage Control Action Management Software (DCAMS). DCAMS provides the visual link needed to monitor and direct the DC effort. Figure 21 shows a picture of a DCAMS display.

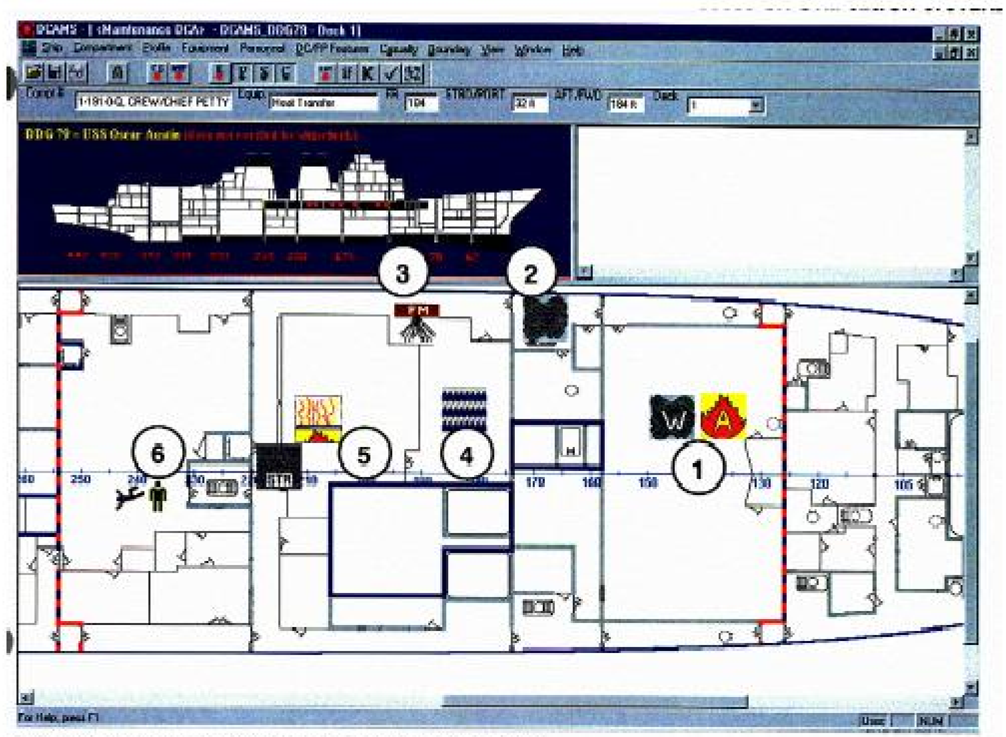

Figure 21. DCAMS Visual Display [30]

Various versions of the visual display are in use, but all of them only have minor differences from Figure 21. Design of the control or base units has not been as much of an issue as the portion of the system to be given to the individual.

F. MOBILE PERSONNEL DISPLAYS

The next foreseeable step in the advancement of damage control is integrating the individual sailor into the system. With wireless technology becoming more reliable, options for linking members of the DC party have changed. Prior to this point, as mentioned above, communications have been handled by the use of soundpowered phones and portable radios, with the standby message blank in reserve. The widespread use of text messaging and picture email software has changed the view on the future of communications. The difficulties of voice communications can easily be lessened by moving to a visual-based message system. Visual based systems have been in use in DC already, through message blanks, and have transitioned into the symbols used in DCAMs. Although the purpose for the visual system can be understood, the method of applying it to the individual sailor is under debate.

G. SOLUTIONS AND PROBLEMS

The current push for a launch platform has been centered around the Palm Pilot™ type of active matrix display whose visual and graphical capabilities makes it attractive for this use. This technology can then be placed by the use of a strap to the sailor's arm, to the sailor's gear, or in a pocket of the firefighting turnout. There is no doubt that the technology can link DCAMS information to a remote user, but this approach brings both advantages and disadvantages.

1. Advantages of the Active Matrix Application

The active matrix display, with corresponding software, allows for the transmission of the DCAMs screens in a miniature format to the individual user. The user will then have access to all data which have been input or collected by the system. The sailor can then be directed by use of an Instant Messenger ™ type of format to accomplish tasks or be sent to a specific location by the DC supervisory structure. The technology will allow the individual to then relay messages back by use of a stylus or on-screen keyboard.

The idea is very attractive to the Navy for a number of reasons.

- It will be an extension of the DCAMs system which is proven to increase the effectiveness in combating onboard casualties.
- The amount of effort needed to bring the sailor up to speed on the technology will be substantially less, since a training program is already in place aboard ship.

- Makes use of visual messaging and will free up shipboard voice communications and lessen bandwidth use.
- Enable the command structure to direct the individual sailor down to the smallest detail.

There are also other advantages in the use of active matrix displays in DC applications. The above are the big picture items that sell the idea - anyone who has been in a supervisory role with respect to a DC organization will agree with the list. Issues, however, arise when looking at the DC communication problem from the DC Locker Officer position and down.

2. Disadvantages of the Active Matrix Application

a. Opening Overview

The overall premise of the Palm Pilot ™ application for communications looks excellent. Unfortunately, there exist too many disadvantages that are not apparent when looking at the issue from the overall supervisor view. The driving factor to date has been to find a way to control the entire evolution through a system that will tell personnel in the DC organization their options and allow them to tell the sailor what to specifically do. No one will argue that when a trained technical expert is controlling the evolution, in a single supervisory basis, the outcome will be the preferred outcome. This is not the case onboard a Naval ship. Until the reality of a single director comes into play, the current thinking, when applied, will correct some, but compound the majority, of DC problems that already exist.

To outline the disadvantages effectively, the overall concept that is imperative behind shipboard DC, must be in the forefront. That concept is:

TO GET SAILORS FROM POSITION A TO POSITION B,
SO THEY CAN DO THEIR JOB

The concept comes from the practical experience of being on the deck plate fighting a fire and experiencing where confusion and evolution disconnects occur. A sailor knowing "what to do" has very rarely been the problem when looking at Afloat Training Group (ATG) Main Space Fire Drill (MSFD) discrepancies. The Fleet has been very effective in training personnel on procedures and response actions and ATG discrepancies have always been in the area of:

- Lost communication (with Investigators/Attack party/On Scene Leader/ Damage Control Central)
- Repair Locker could not effectively direct Investigators to reported areas of possible damage
- (Investigators/ Isolation Team/ Fire party) did not have a path to follow to the damaged area.
- DC members broke and crossed fire and smoke boundaries

Obviously, the experience of the crew in performing response actions will determine the size of the list ATG generates, but the above issues seem to occur independently of the experience level of the crew is. DCAMs is an exceptional technology that needs to be onboard ships, but options in linking the system to the sailor need to be analyzed. This is to ensure that the device which will be chosen for use will provide the total desired performance and not only minimal help.

a. Material Issues

There are various material issues that are of significance for the placement of an active matrix display of the Palm Pilot ™ variety on the DC team. The first issue is the most apparent - that the display is not going to be the standard model off an electronics store shelf. The off the shelf displays are already at substantial cost and that cost will be increased since the display will need to be hardened to withstand the environment and the constant "rough use" it will have to endure. This hardening will increase unit cost and is unavoidable since the price of the display dictates that it be able to be used for the lifetime of the system. The longevity of the unit is based on the fact that there is just not enough funding available to assume that there will be replacement of these units fleet-wide on a quarterly or yearly basis. The lifetime versus cost is an issue of notable proportions.

The next material issue which is an ongoing concern, is pilferage. The active matrix displays, to reduce cost, will be more performance based versus military specifications based, or otherwise commercial off the shelf (COTS), with respect to its ability to be programmed or have software uploaded. This opens up the possibility of modifying, reloading, or erasing applications for the equipment to be used for personal use. To those who have not had the experience of being stationed on a ship, this may seem astonishing. If sailors are willing to remove AA and other size batteries out of DC gear for personal use, the idea of taking a display for a personal organizer is not far fetched.

b. Usage Issues

The active matrix application, if brought down to the very basic base process, could provide some reasonable measure of success. The unfortunate problem is that it will not be a simple application like a ship map and DC symbols. Current thinking is to have it fully integrated with DCAMs to have its abilities on the deck plate, apply a text messaging system for communications, and whatever other new ideas evolve before acquisition. Two main problems could arise from this DC application. First, the system will perform during an advanced technology concept demonstration, but the shift to the fleet may ask too much of a sailor. There is a point at which the load of expected ability of the individual sailor falters; the text messaging application could be beyond that point. The physical difficulties of the sailor with communications during damage control operations, focusing on breathing, survival, and the immediate task before them, and failures in using the portable radios or other means of communication effectively which were referenced in an earlier section have not gone away. The desire for the system to enable the sailor to actively look up and use solutions or response actions on DCAMs, assimilate all the information that DCAMs will provide, and read / comprehend/ send text messages is a lot to ask even from an experienced senior sailor. Linking DCAMS to the individual sailor does not seem to make the firefighting situation easier, but appears to be adding another layer of complexity.

A second issue comes from the idea of having a text messaging portion added to the application. The DC organization is set up with the Damage Control Assistant (DCA) directing the Locker Officers, who in turn direct the Locker Leaders, Investigators, On Scene Leader (OSL) and the rest of the locker personnel. The DCA makes his or her decisions and directives by following DC checklists, and the various DC documents and manuals which they have been trained to use. Other individuals that are available to receive information or provide advice, if needed, are the Engineering Officer Of the Watch (EOOW), Chief Engineer, and of course the Commanding Officer (CO). These other officers though, for the most part, are not directing DC efforts and are involved in other action to fight and save the ship. The DCA will make regular reports during the DC evolution to these Officers in order for them to have knowledge of the situation. DCAMs will now allow these individuals to see in real time what is going on as the DCA makes inputs into the system as data become available.

This real time conveyance is great since the overwhelming calls from them, especially the CO, wanting to know the status of the damage and what is going on, will be eliminated, therefore allowing resources to respond to other issues. The downside is that micromanagement is alive and well within the military, even though we have every intention not to do it. In circumstances like a main space fire, the bridge (ie. the CO and watchstanders) are relying on a junior officer (the DCA) for all damage control information and to direct DC personnel correctly in order to save the ship. The text messaging option will now allow someone in the top of the chain of command to direct someone at the deck plate level bypassing anyone in between whenever they choose to. The argument from those outside the DC organization is that the CO or other senior officers need to intervene when they are aware that something incorrect is going to be done. That statement is absolutely right, but major damage scenarios are practiced and trained over and over, and the manner of action has been well thought out in advance. The problem is that now no one has to wait for the DCA to provide information, they now have the ability to hit the deck plate sailor directly with: What are you doing? Where are you? What is going on? This stepping in and micromanagement will be a very hard thing not to do and the temptation will get the best of many in the Fleet. Of course, this may be a moot point, since the sailor may not be able to follow or respond to text messages from anyone when in the midst of combating damage.

H. WHAT CAN BE CONCLUDED

The issue of DC communications when considering all its various entangled aspects is not simple. What needs to happen is that a reasonable solution that both increases DC performance and minimizes the addition of complexity. Some of the guiding factors would be the following:

- Low cost per unit
- A unit that is rugged and can withstand the environment
- Reduces voice communications
- Relays information to the sailor in a manner that is direct and simple to understand
- Does not hinder sailors (i.e. weight and or size)

The active matrix approach to date has been the only style of equipment discussed, and a stripped down active matrix display may end up being the best solution. Until options which take advantage of other technologies are brought forward, a true analysis of alternatives cannot be completed which will compare and balance known requirements.

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VI. APPLYING LIGHT EMITTING POLYMERS TO SHIPBOARD DAMAGE CONTROL

A. INTRODUCTION

Display technologies in the current market range from the simple and cheap incandescent bulb behind a graphic overlay to the highly expensive flat panel high definition plasma display. With such a selection to choose from, matching an application to the correct technology is becoming an increasingly difficult task. Light emitting polymer (LEP) displays offer a viable alternative to the active matrix style, when an application calls for information to be sent in a simple visible format. The following sections will describe a LEP display for use in the area of shipboard damage control and firefighting. This application is provided to give additional options during the analysis of alternatives and the final selection of a display baseline for damage control.

B. LIGHT EMITTING POLYMER DISPLAYS

Manufacturers of display technologies have been developing LEPs with the intention that using these types of polymers in displays will be the next forward step in visual graphics. Companies like MicroEmissive Displays, Lumation, Cambridge Display Technology and Dow Chemical have realized the potential for LEPs and their ability to provide increased processing flexibility while reducing manufacturing costs. A comparison between liquid crystal displays (LCD) and PLED production lines can be seen in Figure 22.

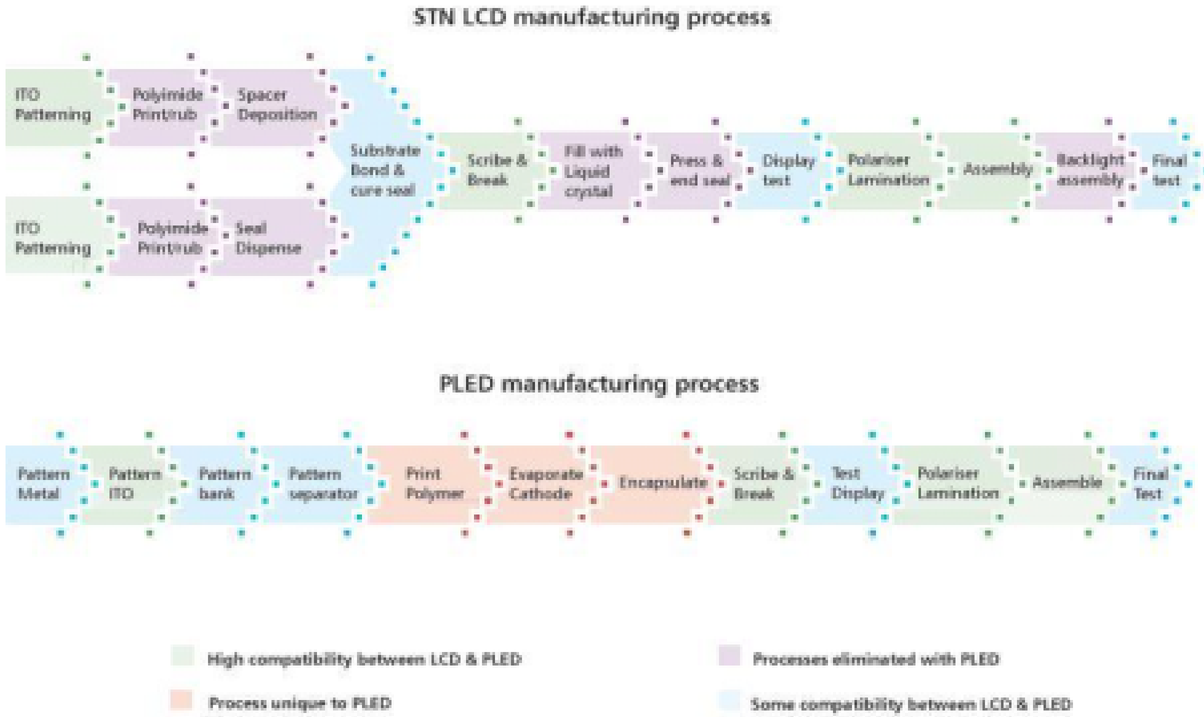

Figure 22. LCD verse PLED manufacturing process comparison. [34]

The polymer materials also have some other advantages that make them appealing in areas other than cost. The Display Technologies group of Dow's Advanced Electronic Material submitted a press release in November 2003 stating that "LEPs are the critical light emitting material in PLED displays. PLED technology produces bright, high-contrast, low voltage emissive displays, providing many advantages over incumbent display technologies, such as traditional liquid crystal displays (LCDs)." Having a flexibility in processing, the challenge in LEP displays is to find a manufacturing method that is reliable and best fits the application in which the device will be used.

1. Manufacturing and Design

The manufacturing process consists of many parts, including substrate preparation, anode / polymer / cathode, deposition, solvent extraction, and encapsulation. This is a simplified list, but all aspects of PLED display production that are applicable will be discussed. The flexibility in processing of the polymer makes it almost impossible to describe all manufacturing processes. The methods which companies have taken have been dependent upon the capital equipment which is owned by the facility, the method which best fits into their other production lines, and the display design which their internal research group believes to be most advantageous to the company's envisioned display application.

The process of depositing the polymer can be spin coating, doctor blading techniques, ink jet printing, and a variety of other printing processes. Each of these methods are proven to be able to place the polymer on the substrate effectively. The cost aspect then comes into consideration when the printing process has been selected, and issues concerning polymer specific requirements and the intended device have to be addressed. Specific polymer properties can increase the cost of the capital equipment needed for deposition. LEPs currently range from those which need to be under vacuum to prevent water or oxygen from permeating the polymer while it is placed, to those which need specific cooling or heating requirements, in addition to a vacuum, for setting or removing excess solvent. The ability to place the printing equipment, either fully or partially under required conditions, is not just difficult, but costly. The next issue is the cost of encapsulation and of the components around the polymer. To use an analogy, a wall can be made simply by using a 2 by 4 wood frame and plywood, or it can be made with a 2 by 4 frame, plywood, sheet insulation, vapor barrier, drywall, paint, and siding. In constructing the wall, the builder gives consideration not only to construction preference, but to what the wall is for. In display fabrication the same is true, and some of the devices and methods being introduced into the market are shown in Figures 23 and 24.

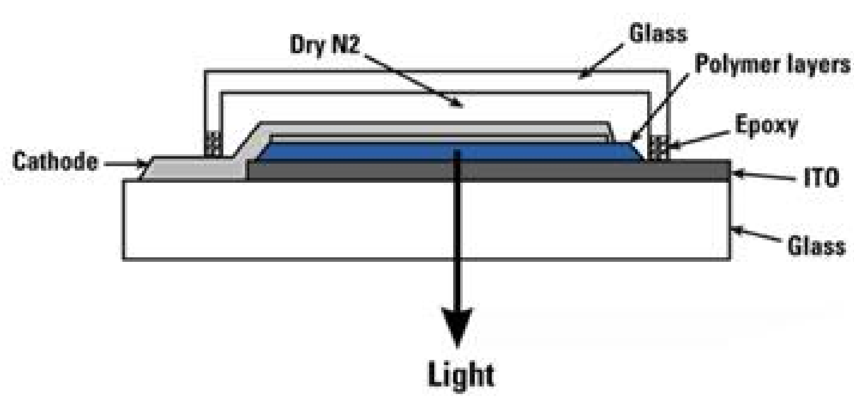

Figure 23. PLED designed by Dow Chemical AEM [33]

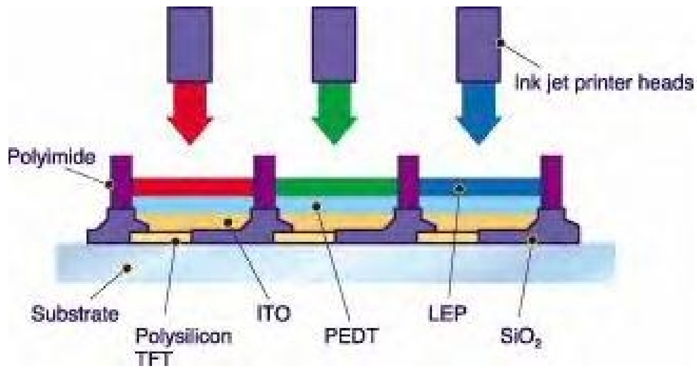

Figure 24. Ink jet PLED designed by CDT [34]

The two pictures above show different approaches to the fabrication of a display. With each, it is important to note is the level of complexity of the components around the polymer. The Dow design is a glass encapsulation buffered by dry nitrogen. It is sturdy, but has costs attached for manufacturing and placement of the glass top layer along with injection of the inert gas. The CDT design shows how a display can be made by ink jet methods, but, as one can see, to provide the resultant visual picture substantial cost is absorbed to make the multi-material structure to encapsulate the polymer. All the various methods of fabrication have their advantageous and disadvantageous, but the driving factor as mentioned before is the application with some thought to cost and longevity. The next section will describe the method of fabrication and device components for the proposed technology to be used for displays in shipboard DC.

C. ADD-VISION DEVICES

Flexibility in processing of polymer displays had enabled various companies to pursue a wide variety of possibilities. The selection of a manufacturing process in making the displays for use in shipboard DC has to meet some of the requirements of the earlier section on DC communications. The two that relate to the manufacturing process and have the highest priority are:

- Low cost per unit
- A unit that is rugged and can withstand the environment.

The method of fabrication by Add-Vision would provide the Navy with one possible solution that takes into account both of the requirements. The solution was not found in one particular innovation but though various aspects of the fabrication process.

1. Fabrication and Cost

The process of fabrication is simplified by using low skill and low cost capital equipment. The basis for this is the light emitting polymer that was developed by Add-Vision. The LEP can be processed in an ordinary environment, in plain air, with no need for specialized clean rooms or inert gas, such as the nitrogen. This enables the fabrication to be done by a patented screen printing process for both the top electrode and the polymer.

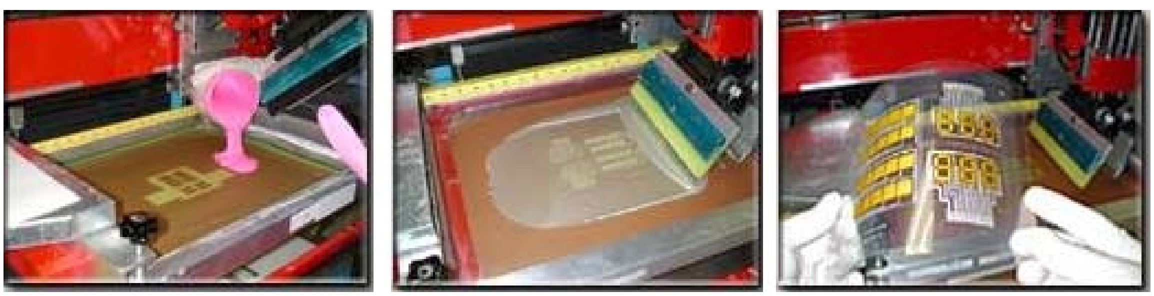

Figure 25. Add-Vision screen printing of polymer and top electrode. [35]

This is modeled after the screen printing process use in creating thick film electroluminescence or membrane switches. Although Add-Vision uses screen printing, the transfer to other printing processes can easily be achieved [35].

The step by step manufacturing process can be done on one piece of equipment instead of a line of machinery. The design of the display can be done by the use of a multitude of graphics programs such as PhotoShop ™. Figure 26 gives an overview of the process.

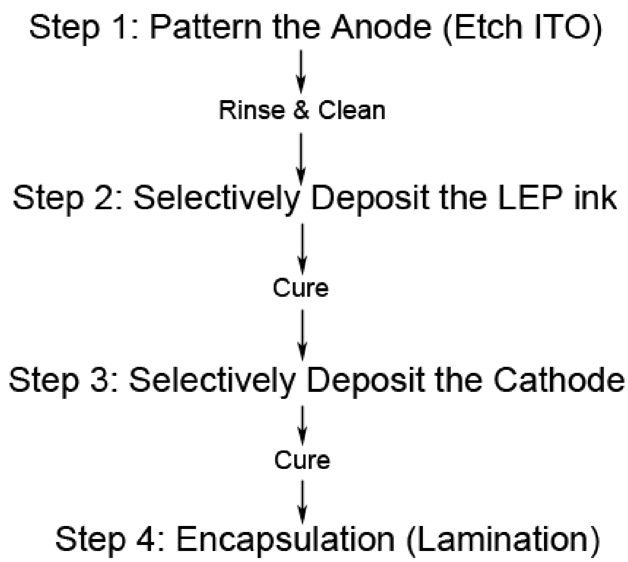

Figure 26. Add-Vision manufacturing process [35]

By having the ability to produce displays in this manner, a reduced capital investment can be passed on to the customer in the form of low unit cost per device. Currently the cost is 10 to 20 cents per square inch of active area. For a production line which can make 25,000 square feet per month, the cost of capital equipment of the production line is under 1 million dollars and represents 15 to 18 million in revenue [35].

The selection of a flexible plastic substrate and encapsulation also is a driving factor in reduced unit cost. Unlike the devices in Figure 11 and 12, the polymer and top electrode (cathode) are printed directly on the Indium Tin Oxide coated plastic substrate, then encapsulated with a flexible plastic as well. The curing of the polymer in an air environment and the printing process eliminates the need for precision manufacturing of multi-material ink jet wells or placement of glass encapsulators. This is aided further by the low skill level needed for the equipment operator, providing some payroll savings.

D. APPLICATION TO FIREFIGHTING

The technology described in the previous section is an ideal fit for a mobile display for a sailor tasked with DC or firefighting duties. The low cost of the unit makes it ideal for a number of reasons. First, outfitting of fleet ships can be done at one time instead of a phased introduction. Display technologies that carry a hefty price tag cannot be purchased all at one time for fleet-wide dispersal. Secondly, the low cost of a few dollars per device enables the replacement of units that are damaged with little impact to program funding. Lastly, the units can be altered by re-creation of graphics, and new units can be printed with no additional capital investment. These items are of great concern since when gear breaks, it needs to be replaced immediately. Unfortunately, replacement of costly gear is difficult to do fleet wide in an ongoing process. Equipment that is functional and can be easily replaced is a bonus to the individual activities.

An aspect that is not always considered is that the sailor, during firefighting evolutions, is weighted down with protective clothing and gear. Figure 27 shows some of the personal protective gear that is worn.

Figure 27. Firefighting Ensemble and Self Contained Breathing Apparatus

The weight and bulkiness of this clothing and of the carried gear can become cumbersome. The display will be another piece of equipment that needs to be carried along as well. This dictates that the display has to be not only light, but unobtrusive. The flexible nature of the Add-Vision display just does not aid in placement, but its thinness (Figure 28) will not add additional bulk to the sailor.

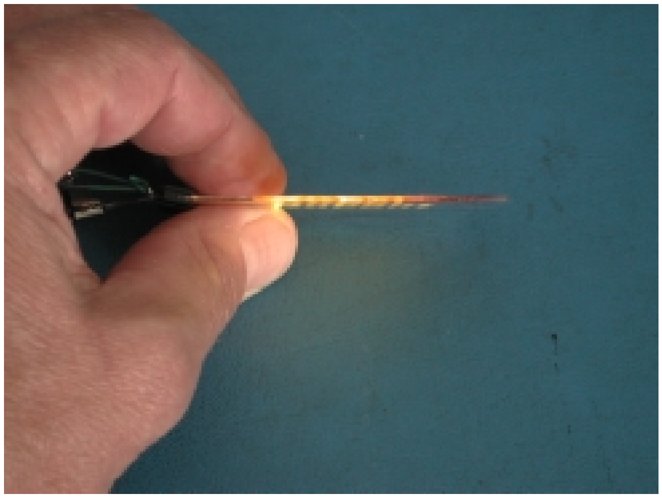

Figure 28. Display Thickness [35]

The display can then be attached to any portion of the sailor within visible view that is flat or semi-flat. This will provide the ability to utilize the display without it being a hindrance to performance of firefighting tasks. With a desired display technology decided upon, the last step is to formulate and fabricate a model to fit the firefighting application.

E. DESIGN OF A PROTOTYPE

The design of the prototype will focus on a visual communication method that can transfer information to the firefighter in a simple and direct manner. The Add-Vision fabrication process and light emitting polymer will provide the backbone for the device. As the prototype is described, additional information will be given on the significance of each step with regard to firefighting, and if applicable, why a decision was made to use a specific pathway.

1. Display Structure and Driver

The display follows the needed components for PLEDs and will have the following structure and layers.

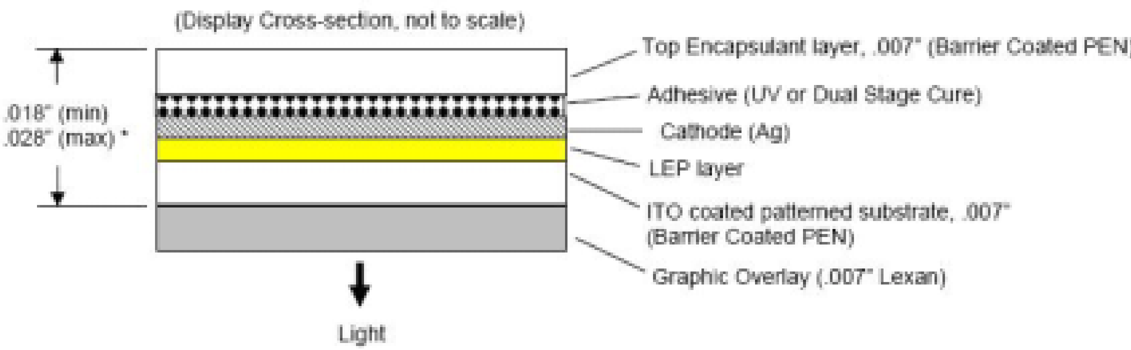

Figure 29. Add Vision prototype fabrication [35]

As can be seen, the prototype utilizes the screen printing fabrication process which produces a flat layer device. Figure 30 shows Figure 29 in actuality.

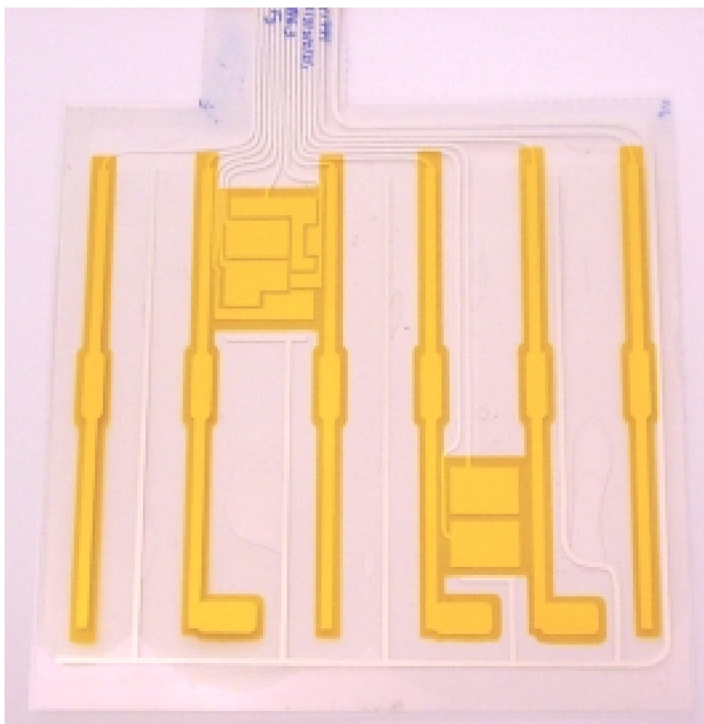

Figure 30. Prototype actual fabrication

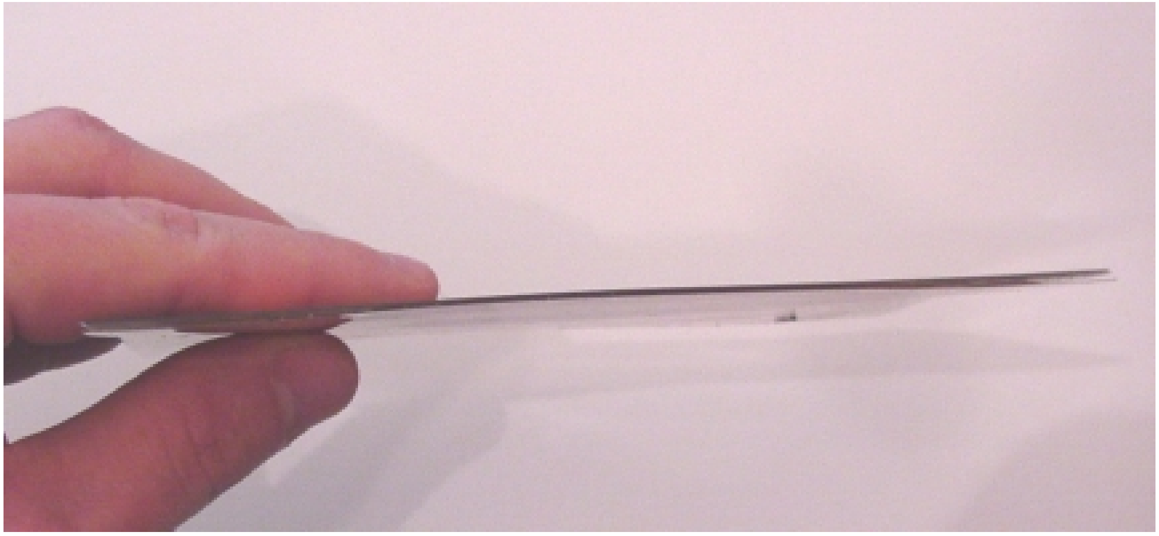

Figure 31. Prototype thinness (graphic overlay is attached to polymer structure)

In order to demonstrate the technology without ensuing additional cost, a single polymer color is used and various color graphics are provided by the graphic overlay (Figure 31). Additional polymer colors require multiple screens during the printing process. Since the number of colors does not aid in the demonstration of the technology, the decision to forego the extra cost was made.

The display driver for the purpose of demonstration was made simply by use of a programmable read only memory (PROM), current generator, power source, and a 21 channel distribution network (Figure 32).

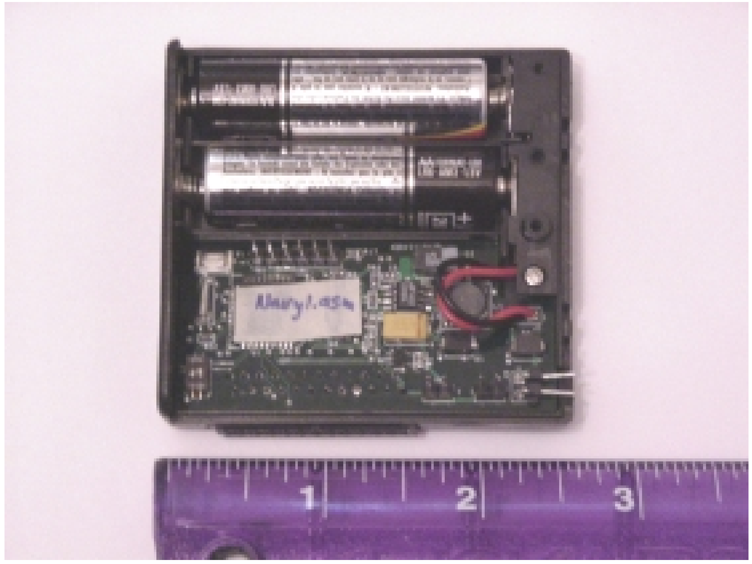

Figure 32. Display Driver

The driver through a binary method, either turns on (sends current to) or turns off (removes current) from the individual channels to activate or deactivate portions of the display. The amount of current needed to be sent to the active area for illumination is dependent on the area which can be seen in the following relation.

$$2.0 \text{ mA/cm}^2 = 100 \text{ cd/m}^2$$

The 3 volt input voltage of the power source for the prototype is provided by 2 AA batteries for convenience. The size of the battery is dependent on the amount of device use that will occur before a changing out the power source is needed. A smaller or larger battery can be used depending on expected lifetime of an evolution and the amount of recurring evolutions. The driver required for shipboard use to receive data will be discussed during integration into the ship systems.

2. Layout

The layout of the device needs to be of a style such that information can be given to the sailor in a direct, understandable, and simply format. The concept is to use a predetermined template in which portions will be illuminated to direct actions and relay information. The selection of the most effective overlay can be debated at a point farther along in the development process, but can range from the Message blank seen in Figure 20 to a modification of a NAVSEA basic DC training picture in Figure 33.

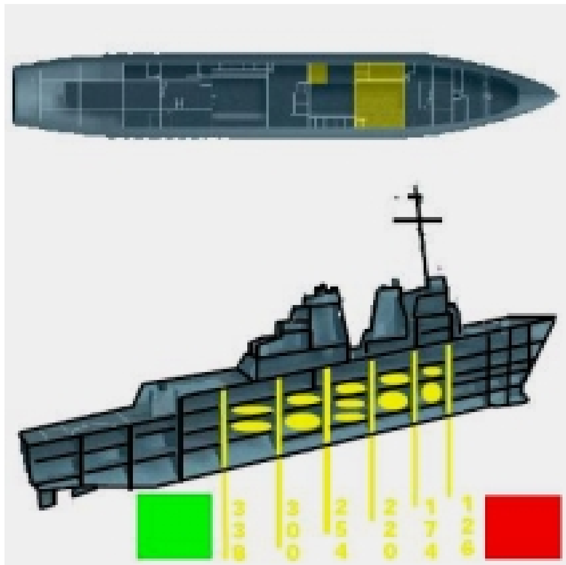

Figure 33. Possible layout from modified NAVSEA picture

The purpose of the device is to transmit data and direct personnel to combat a fire, so the most feasible idea would be a schematic of a ship. The schematic could be illuminated to indicate the space where a casualty has occurred, pathways through the ship which should be taken, fire / smoke boundaries, and an indicator of the type of casualty. The concept is to allow the sailor to look down at the display and see the status of DC efforts, where he or she needs to be, and how to get there.

As a first run at a layout, a ship schematic was created from a flooding effects DC plate of an Arleigh Burke Class, Aegis Guided Missile Destroyer. The layout is only of the main deck and the second platform between frames 338 and 126, and is shown in Figure 34.

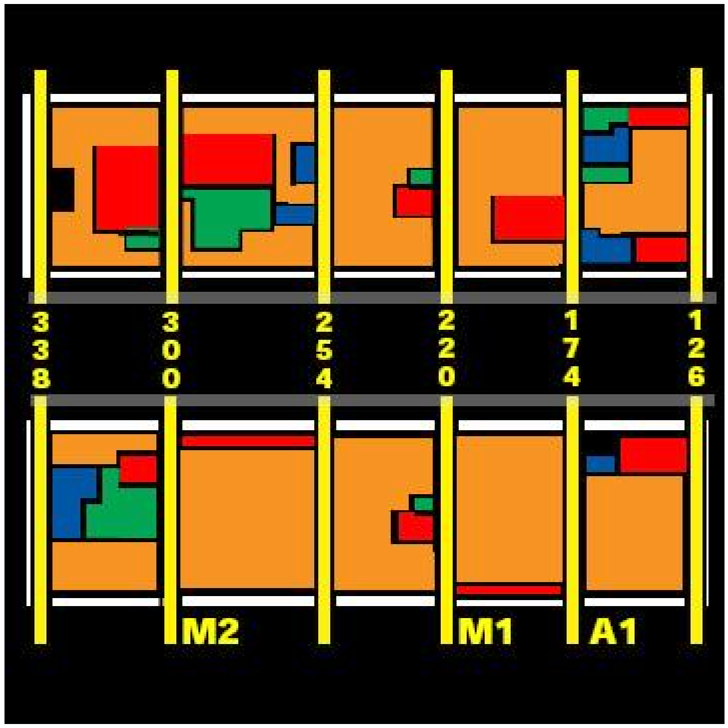

Figure 34. First Run Prototype Layout

The layout depicts the various spaces on those decks with frame numbers clearly seen. The spaces are not labeled with the exception of M2, M1, and A1 indicators for the Main Engine Room 1, Main Engine Room 2, and Auxiliary Machinery Room 1. In future iterations more space labeling will be done with the addition of symbols for different classes of fire and smoke. A to-scale deck layout can also be developed to enable pathways through the ship to be illuminated so sailors can be directed to a casualty by use of the safest route. Even though this version may not have all the needed features, it will be able to demonstrate the technology and potential use for firefighting onboard Naval ships. During firefighting, an illuminated and blinking main engine room with illuminated frame numbers is a clear message to the sailor of where the casualty is. Earlier it was discussed that a sailor will be focused on breathing and the task at hand and may not be able to use or understand voice communications. This method takes a portion of the human element out and builds off the proven message blank concept. Since the display is flexible and thin, it can be strapped by use of Velcro to the arm of a firefighter, giving the ability to glance down through the breathing apparatus face piece and gain information visually.

3. Illumination

The question of illumination and whether a light emitting polymer can be bright enough in the various shipboard environments is the most noted concern. The polymer is able to produce a brightness up to 300 cd/m^2. This value is on a scale that is large enough for the display information to be seen at various exterior light conditions. Pictures of the actual device operation provide evidence that the illumination value is acceptable. The following images were taken in complete darkness at a distance of 2 feet and depict actual operation.

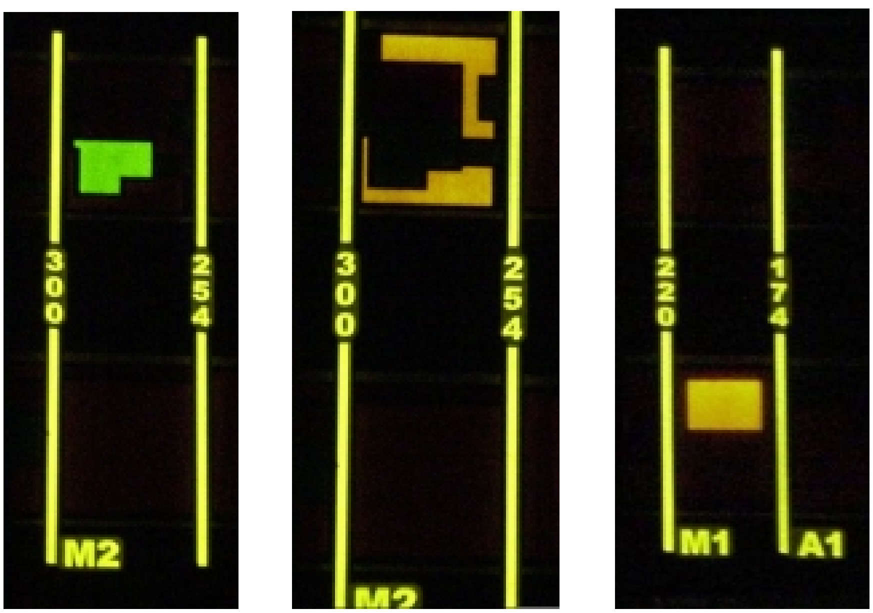

Figure 35. Prototype pictures in complete darkness

Images were also taken at various light levels to show the prototype in operation at realistic conditions during firefighting.

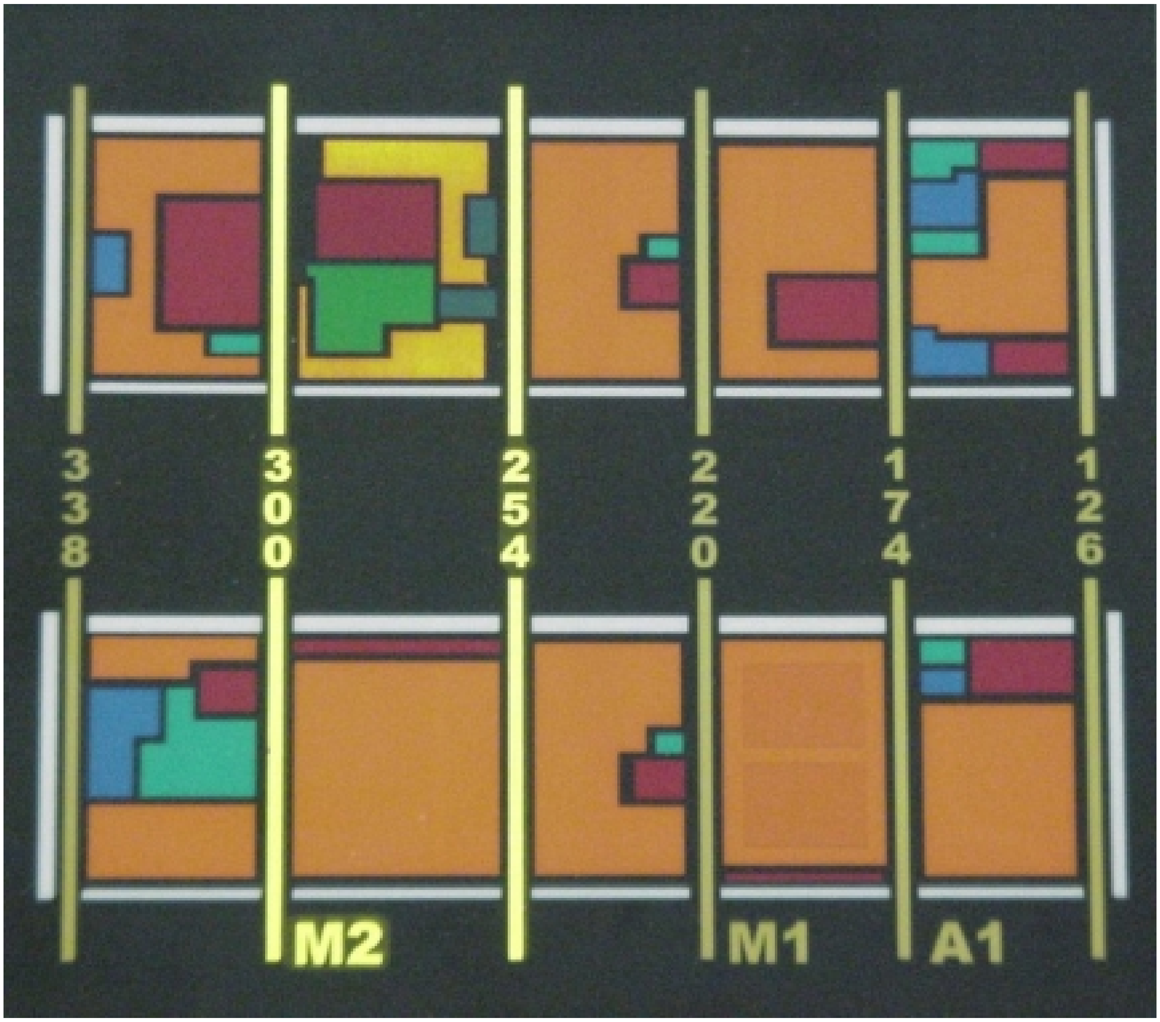

Figure 36. Prototype operation A

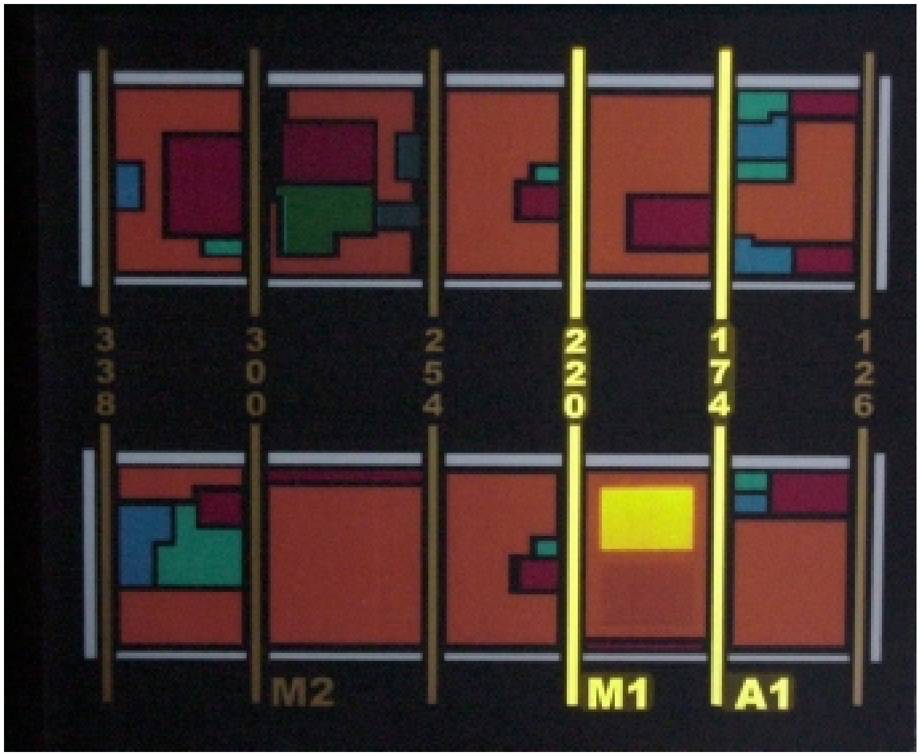

Figure 37. Prototype operation B

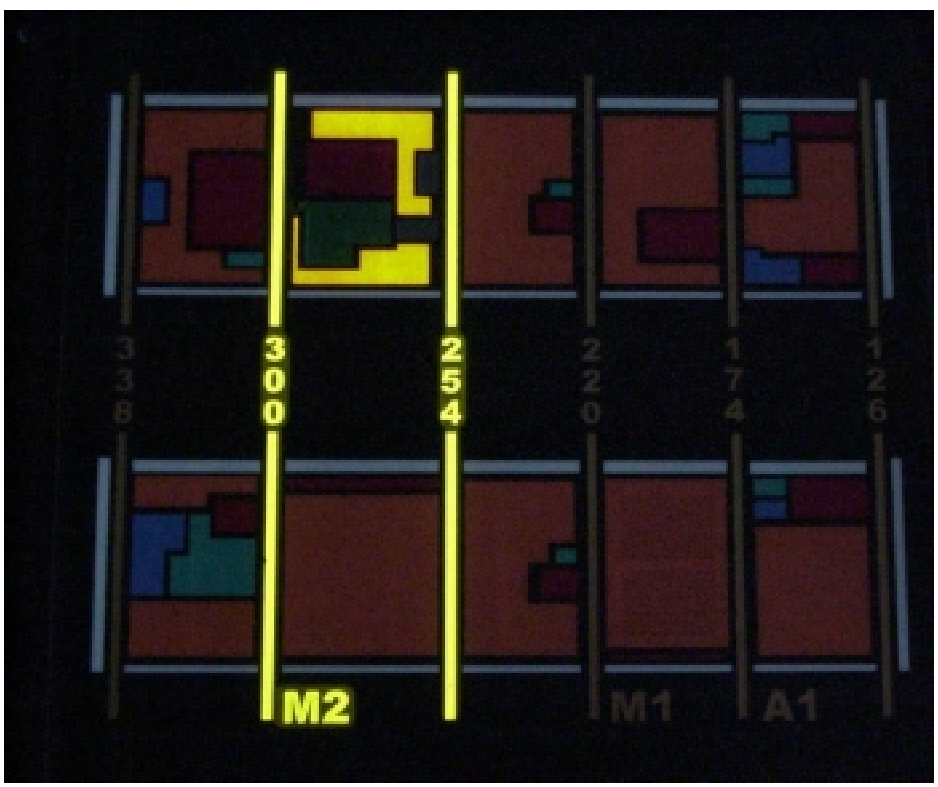

Figure 38. Prototype operation C

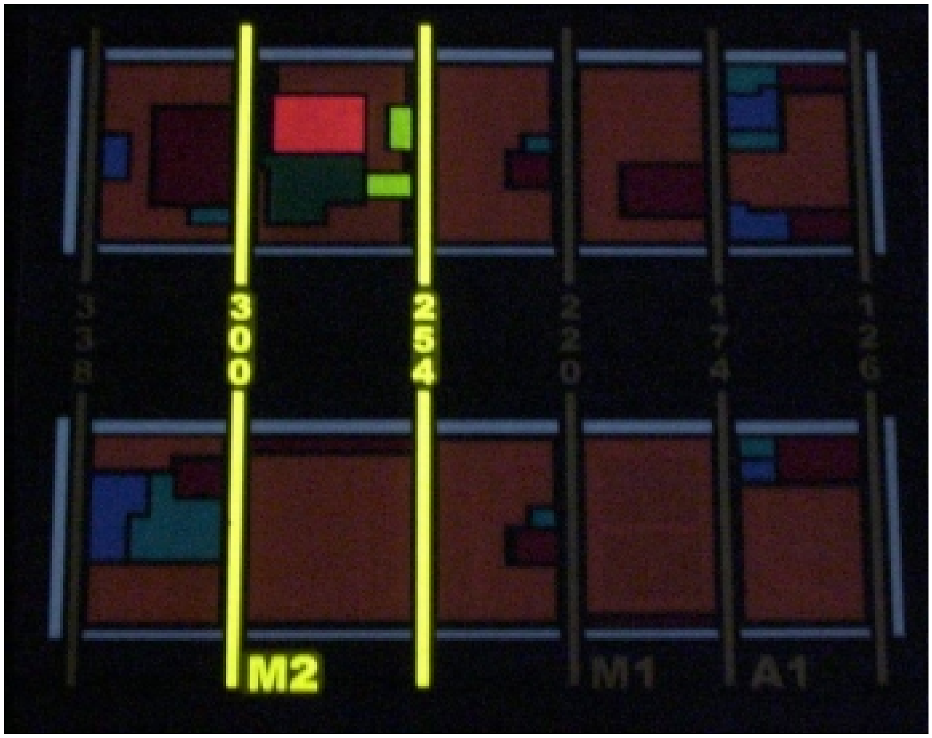

Figure 39. Prototype operation D

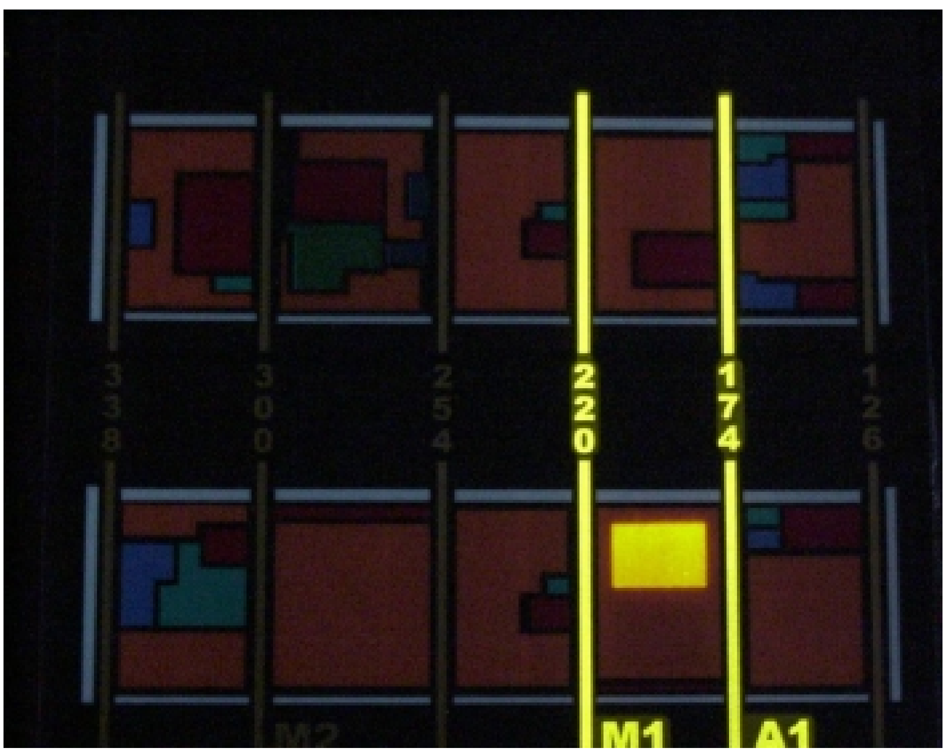

Figure 40. Prototype operation E

In all the pictures the frame markers and numbers are clearly seen, along with the space of interest. Although the pictures are static, and it cannot be seen in the above photos, the indicator for the space does blink and draws attention to desired location.

4. In the Firefighting Environment

The challenge for any piece of technology is its performance in the actual operating environment. During firefighting, extreme temperature gradients and thermal currents exist which places stress on all gear. In an effort to provide information on the light emitting polymer's ability to work in such an environment, a field test was conducted. The field test was preformed at the 19F3A firefighting trainer at the Naval Firefighting School in Newport, Rhode Island on the 8th and 9th of February 2005. The trainer in Newport is a multi-function cold weather trainer that provides team training capability on shipboard fires including engine rooms, bilges, galley, berthing areas, laundry, storage areas and electrical equipment. The operators of the trainer have the ability to produce fires on multiple levels and spaces, selectively or all at one time. The structure of the facility consists of steel rooms within a concrete and masonry building. Although the ceiling height of each level is more than what is found onboard naval vessels, the layout, passageways, and hatches are closely identical to ship structure.

The polymer display during the test did not have any difficulty of operation. The display worked as designed throughout the transition from the outside environment to the inside environment of the trainer, and then back out. The device was first operated outside for considerable time in the winter Newport temperature of 31 to 34 °F, before entering the trainer. While in the trainer, the display was operated for approximately 30 minutes within a temperature span of 219 to 265 °F before returning to the low 31°F outside. Although no humidity indicator was monitored, the inside atmosphere of the trainer has a high humidity due to the steam generated by the discharge of firefighting water.

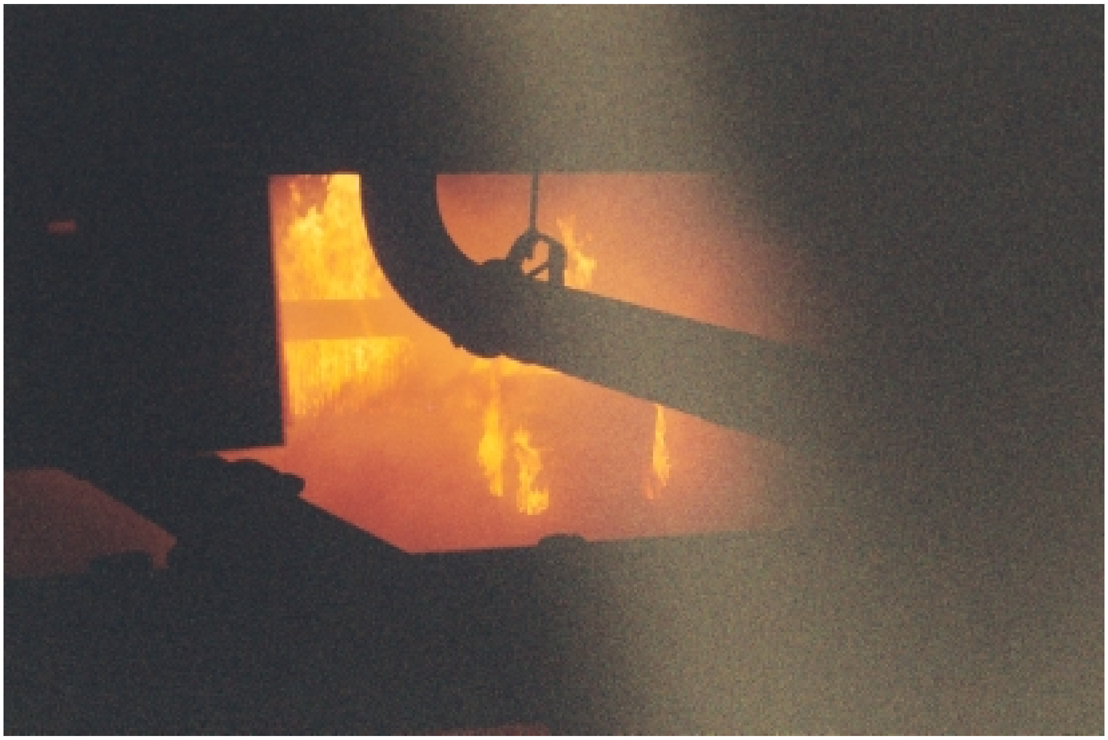

Figure 41. View from within the Newport trainer

Figure 42. Picture showing display in operation during a firefighting evolution

The test was conducted on two separate days with the same device, and the device continues to operate to date. The display proved that the technology can transit between various environments, including firefighting, and operate effectively with no visible loss of illumination or polymer efficiency.

To get an objective point of view of the device operation, the sailors stationed at the trainer in Newport were given the display and asked for their opinions. During and after the test, instructors from the Fire School commented that the display was bright and they had no difficulty seeing the display graphics, even in the heavily smoked out spaces. The concerns that they had were identical to those mentioned earlier in this paper, mostly dealing with the thought that more bulky gear is going to be placed on them. The general feeling was that they were not sure about a ship display on the forearm, but the polymer display (weight and flexibility) would be more appealing than a Palm Pilot™ style. One instructor noted that consideration should be given to making the display look more like the current message blanks which are being used, in lieu of a ship schematic. Overall, the test was deemed a success and proved that the polymer display can stand up to the rigors of the firefighting environment.

F. SHIPBOARD TRANSMISSION

The light emitting display is operated by either the turning on or off of a channel using a simplistic binary controller. A designation of 1 to a channel turns the channel on (current allowed to flow in channel by bias turn on), and a designation of 0 to turn the channel off. In the prototype this is accomplished by the programmable read only memory which is set up to run a preset program to operate the display through a pattern. On board ship, the display will have to be capable of receiving data which will dictate display operations. Since the display is binary, on or off, use of preset pulse modulations can be designed to activate the control unit to place a 1 or 0 to a channel. These pulses can be sent by use of a transmitter which is connected to its own control unit or incorporated in installed systems such as DCAMs. A possible example of this would be using a replica of the LEP display on a Palm Pilot ™ style device, in which by using the stylus, various portions of the LEP display could be activated. With advancements in the power output and size of wireless transmitters / receivers, as evident in the minimization of cell phones and mobile PDAs, application of the technology will not be difficult. The transmitted signal, since it only needs to be pulse modulated to send operational data to the display, can be placed on any desired signal. Having the flexibility of choosing the signal characteristics, unlike some of the restrictions on voice signals, the system can be set up to not interfere with current frequencies or wave functions being used aboard ship currently. Although actual transmitter and receiver design have not been made, current commercial off the shelf technology is believed to be available to meet system needs.

G. CONCLUSION

The application of this display technology to shipboard firefighting is a new concept that has not been previously conceived. The need for a visible communications method that is lightweight and non-bulky, can operate within the firefighting environment, and has a low unit cost is a frontline issue in the area of survivability in the fleet. The light emitting polymer display that was constructed has all of these desired characteristics, even though it was a first attempt at using the technology in this manner. With further refinement, the display will be able to provide the level of performance that is expected from equipment which is to be used in combating casualties aboard ship.

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